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Technical Evaluation and Assessment of CNG/LPG Bi-Fuel and Flex-Fuel Vehicle Viability

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INTRODUCTION

The National Renewable Energy Laboratory (NREL), on behalf of the U.S. Department of Energy (DOE), has had a long-standing interest in advancing the use of alternative fuels for conserving energy and reducing the nation's dependence on foreign oil supplies. Successful application and use of alternative fuels requires that associated environmental issues be addressed. NREL requested that J.E. Sinor Consultants Inc. carry out a brief technical evaluation and assessment of CNG/LPG bi-fuel and flex-fuel vehicles.

Based on that assessment, this report provides a comparison of compressed natural gas (CNG) and liquefied petroleum gas (LPG) supplied to light-duty vehicles. The comparison is then expanded to consider the potential benefits of a vehicle capable of using both fuels in either a bi-fuel or flex-fuel configuration. In accordance with DOE's fuel-neutral approach to alternative fuels, the study is not intended to promote one fuel or the other, but to present an unbiased comparison of the technical alternatives available.

BACKGROUND

NREL is the field manager for DOE's Alternative Fuels Utilization Program (AFUP). The goal of the AFUP is to develop and advance technology that allows optimum use of alternative transportation fuels, while complying with modern constraints such as vehicle emissions. If alternative fuels are to be viable candidates to replace petroleum-based counterparts, their impact on air quality must be demonstrated to be no worse than that of existing fuels, and preferably, they will show characteristics that will improve air quality.

Because of the nation's continuing concern about air pollution, Congress enacted the Clean Air Act Amendments (CAAA) of 1990. The Act's provisions will force broad changes in fuels and vehicles. CNG and LPG are two of the alternative fuels attracting attention because of their potential as cleaner burning fuels and their ability to displace imported petroleum products. Although both CNG and LPG have exhibited potential as alternative transportation fuels, each has some weaknesses compared to gasoline. These weaknesses include limited vehicle range; bulky and costly on-board fuel storage; a limited and expensive refueling infrastructure for CNG; and fuel cost and supply concerns for LPG. Developing a bi-fuel, dual-fuel, or flex-fuel CNG/LPG vehicle is one way to combine the strengths of these two fuels and overcome their weaknesses. Before development of such vehicles can start, an evaluation of existing CNG/LPG vehicle technology is needed. The essential technical advancements needed to capture the ultimate potential of a CNG/LPG vehicle in terms of power, range, energy efficiency, and emissions performance should be determined. Also, an assessment of the potential market and uses for a CNG/LPG vehicle is needed. This study is a first attempt to supply these needs.

In order to accomplish the goals of the CAAA and the Energy Policy Act (EPACT) of 1992, American automobile manufacturers need to make available factory-produced and optimized, dedicated-fuel vehicles that can run on clean-burning domestic fuels such as natural gas and propane. However, manufacturers are reluctant to offer dedicated-fuel natural gas vehicles in the near term, and are offering bi-fuel natural gas/gasoline vehicles instead.

The bi-fuel natural gas/gasoline vehicle defeats many policy goals because:

- There is no guarantee the vehicles will be run on natural gas instead of gasoline.

- Because they must still be able to run on gasoline, the compression ratio cannot be raised to take advantage of the high octane rating of natural gas.

- The gasoline tank and fuel system, whether or not the vehicle draws from the tank, will have all the evaporative emissions associated with gasoline vehicles.

The main reason for consumer reluctance to buy dedicated CNG vehicles is thought to be the limited range attainable (with the same tank volume, a natural gas vehicle will have one-fourth the range of a gasoline vehicle) and the limited number of refueling stations available (only about 600-700 in the entire United States).

There is a potential solution to the above problems that does not compromise the goals of the CAAA or EPACT: a bi-fuel (or flex-fuel) natural gas/propane vehicle. Unlike gasoline, propane is almost entirely domestically produced, satisfying the goals of EPACT. It burns cleanly, and unlike gasoline and like natural gas, propane produces no evaporative emissions, thus allowing vehicles that run on it to qualify as inherently low emitting vehicles under the CAAA. There are between 5,000 and 10,000 retail propane outlets already in place. And propane has roughly 75% of the energy density (and vehicle range) of gasoline instead of the 25% of natural gas. Propane-fueled vehicles were developed as early as 1912 (Smart 1980).

Propane has not been favored in energy policy to date because of a perception that supply is limited. But if it serves only as the "emergency" or "range extender" fuel in a bi-fuel natural gas/propane vehicle, those concerns are relieved.

COMPARISON OF FUEL PROPERTIES

In order to lay the foundation for comparing the merits of CNG/LPG systems against CNG/gasoline systems, a listing of pertinent fuel properties was compiled and is given in Table 1. Any such listing, when examined closely, raises a number of questions about the comparisons between fuels. The major problem is that none of the fuels actually in use are pure compounds. Although the major constituent of natural gas is methane, there are numerous minor components of variable concentration that affect its properties. Similarly, although the automotive LPG sold in the United States is mostly propane, other minor constituents can have significant effects on its properties. Gasoline, of course, is a mixture of hundreds of compounds, and no single one is dominant. The comparisons in Table 1 are between commercial gasoline and the pure compounds methane and propane simply because these are the only consistent data available to represent CNG and LPG.

Table 1 reveals several other problems in making comparisons. Gasoline, being a normal liquid, exhibits a narrow range of properties when either ambient temperature or pressure is varied. It can be assumed, for example, that gasoline weighs about 6.2 pounds per gallon no matter where it may be encountered in storage, distribution, or retail dispensing systems, or within the vehicle fuel storage and metering system. Both methane and propane, however, are gases at normal temperatures and pressures. Their physical properties depend strongly on the temperature and pressure at which they are being stored. Comparisons of energy density or vehicle range have little meaning unless the assumed temperatures and pressures are carefully specified. Yet comparisons in the literature often fail to do this. The vapor pressure and liquid density of propane are shown in Figures 1 and 2. The first figure defines the pressures that will exist in a propane fuel tank as the ambient temperature changes. The second figure shows why propane tanks cannot be filled completely. Some ullage space must be left in the tank because the liquid volume expands significantly if the tank encounters increasing ambient temperatures. Between 27^o and 99^oF, for example, the liquid volume expands by 13%. A tank 100% filled with liquid would be subjected to hydraulic pressures far exceeding the pressures on the vapor pressure curve.

The achievable energy storage capacities in a CNG fuel depend on tank temperatures and pressures as well, but even the ranges used in Table 1 show why CNG vehicles have limited range compared to gasoline. This is a major reason that many vehicle owners and operators prefer to have a two-fuel CNG/gasoline vehicle so that range limitations are not a problem.

CNG AND LPG COMPOSITIONS

Natural Gas Composition

The natural gas vehicle industry is still struggling with the concept of a specification for natural gas composition. The basic problem is that the industry controls natural gas compositions for purposes that have nothing to do with vehicle use. Natural gas as it comes from the wellhead is a variable material, with typical compositions as given in Table 2.

Thus far the Natural Gas Vehicle Coalition's Gas Composition Subcommittee and the Society of Automotive Engineers' (SAE) Fuels and Lubricants Technical Committee have been working on Recommended Practice J1616. This includes limits on moisture dew point, oxygen, hydrogen sulfide, carbon dioxide, methanol, particulate material and propane (Stokes 1993). To supplement pipeline delivery of natural gas during peak demand periods, a number of natural gas distribution companies inject a mixture of propane and air into their distribution systems. The level of propane/air injection varies with peak demands. As much as 50% propane/air and 50% natural gas blend (or nearly 20 volume percent propane) can be injected. This practice affects gas composition by increasing the amount of potentially condensable hydrocarbons, inerts, and oxygen.

Table 1. Comparative Fuel Properties

	Units	Methane	Propane	Gasoline
Molecular Weight		16.04	44.09	
Physical State		Gas	Liquefied Gas	Liquid
Boiling Point	°C	-162	-42	27-210
Typical Pressure in Tank	psig	2,500-3,600	50-190	Ambient
Typical Pressure in Tank	MPa	17.3-24.9	0.34-1.3	Ambient
Typical Specific Gravity		0.13-0.19	0.508	0.74
Typical Density in Tank	lb/gal	1.1-1.6	4.24	6.2
Heat of Combustion (LHV)	Btu/lb	21,502	19,929	18,548
Heat of Combustion (LHV)	MJ/kg	50.1	46.4	43.1
Typical Energy Density (LHV)	Btu/gal	23,000-34,000	84,500	114,000
Typical Energy Density (LHV)	kJ/l	6,500-9,500	23,600	31,700
Heat of Vaporization	Btu/lb	219	183	335
Heat of Vaporization	kJ/kg	512	427	783
Free Vapor-Specific Gravity	ratio to air	0.554	1.522	
Critical Temperature	°C	-82.6	96.7	
Critical Pressure	psia	667.8	616.3	

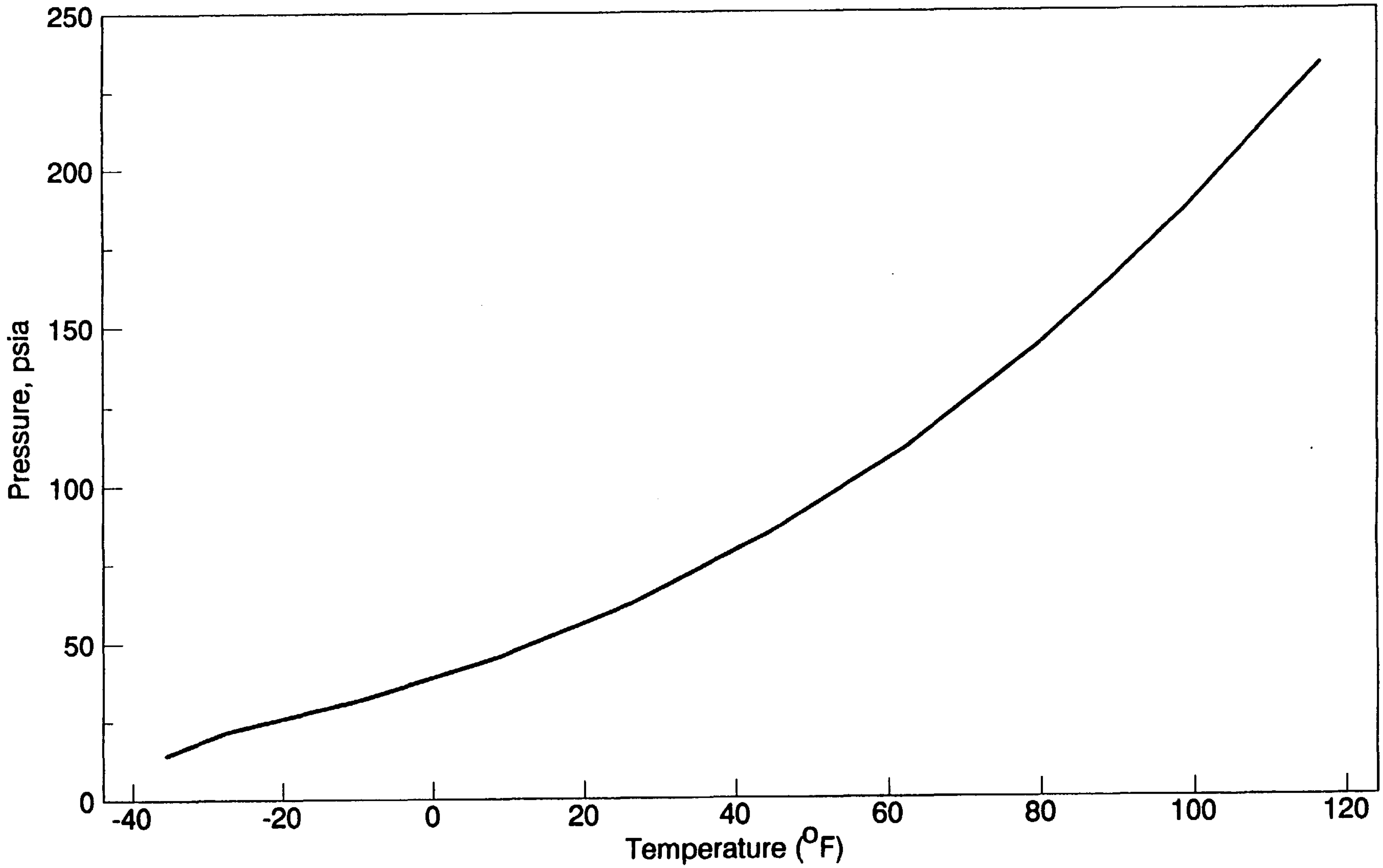
LHV = Lower heating value

Sources: Various

Table 2. Composition of Typical Natural Gases at the Wellhead

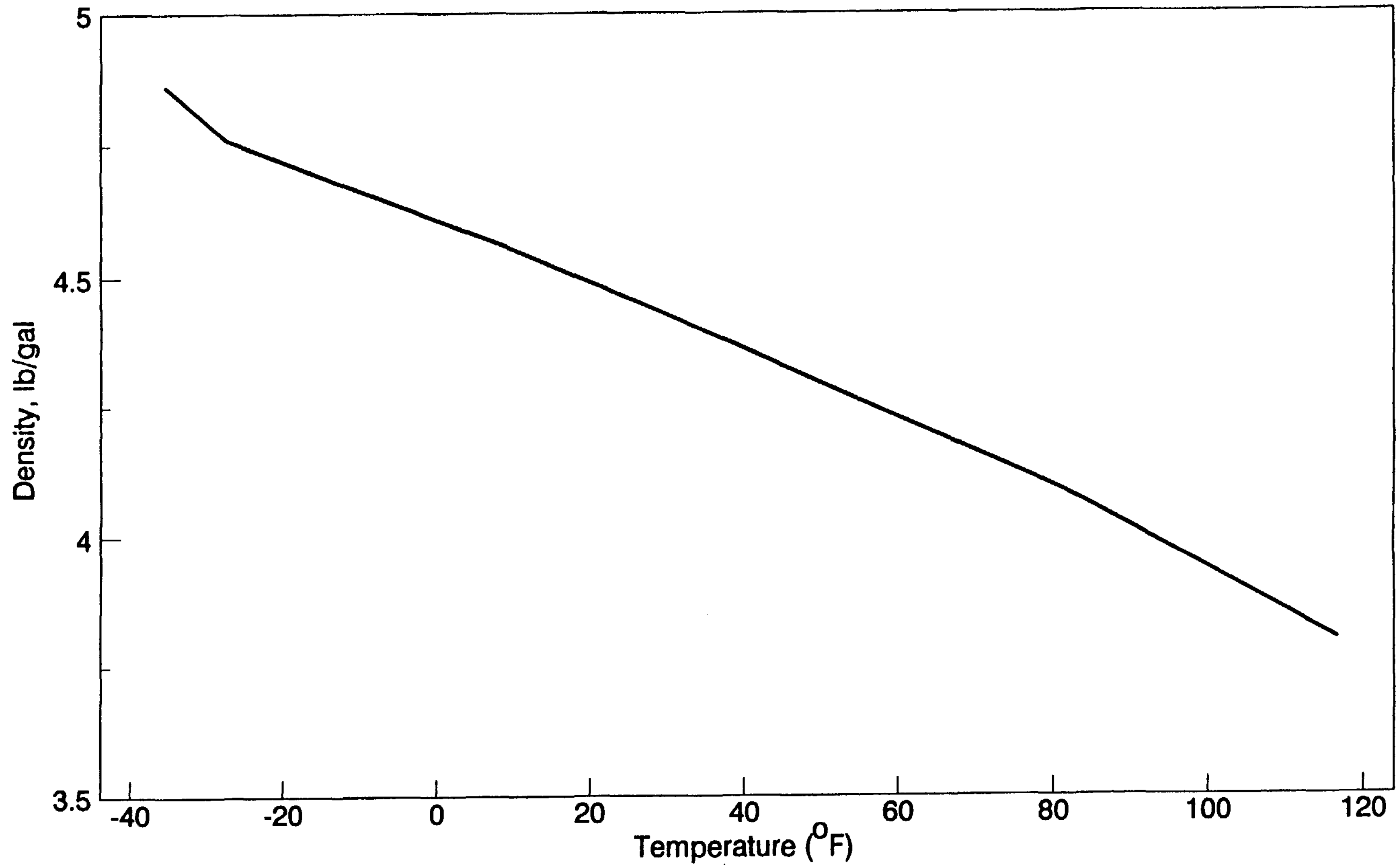
	Location		
Component, Volume %	Salt Lake, Utah	Webb, Texas	Klifside, Texas
Methane	95.0	89.4	65.8
Ethane	0.8	6.0	3.8
Propane	0.2	2.2	1.7
Butanes		1.0	0.8
Pentanes & Heavier Hydrocarbons		0.7	0.5
Hydrogen Sulfide			
Carbon Dioxide	3.6	0.6	
Helium, Nitrogen	0.4	0.1	25.6
Helium			1.8
Total	100	100	100

Source: *Kirk-Othmer Encyclopedia of Chemical Technology*, Third Edition, 1981



Source: Perry et al. 1984

Figure 1. Vapor pressure of propane



Source: van der Weide et al. 1994

Figure 2. Density of propane

Propane has a relatively low vapor pressure (Figure 1) and if present in sufficient quantities, will form a liquid phase at elevated pressures and low temperatures. If liquid hydrocarbon formation occurs, changes in the gas heating value and specific gravity will result. This in turn will lead to changes in the fuel Wobbe number and to fuel enrichment problems when heavier hydrocarbons revaporize. High levels of propane reduce the fuel's knock resistance, and if used in a high-compression-ratio engine designed for natural gas use, could lead to engine failure.

To minimize the potential for these problems, the committees have recommended that the composition of natural gas fuel be such that not more than 1% of the original storage volume will form a liquid condensate at the lowest dry-bulb temperatures and at the highest gas storage pressure conditions.

Figure 3 shows the maximum allowable concentration of propane in volume percent which corresponds to a 1% liquid condensation volume for various low ambient temperatures and highest gas storage pressure conditions.

LPG Composition

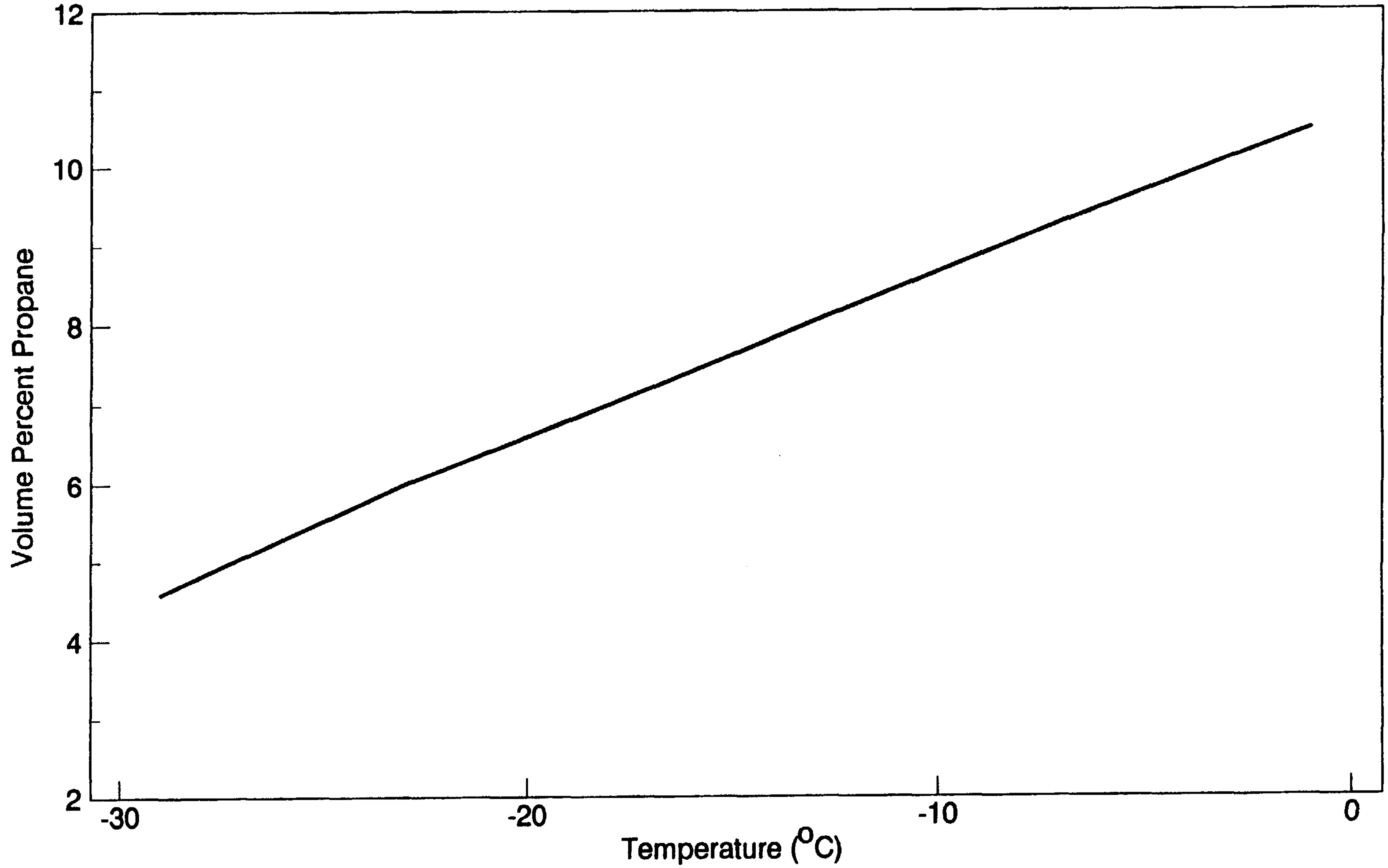
The term LPG applies widely to any mixture of propane and butane--the two constituents occurring naturally in oil and gas reservoirs that are gaseous at normal atmospheric conditions but can be liquefied by pressure alone. Components heavier than butane are liquids at normal conditions and components lighter than propane cannot be liquefied without refrigeration.

The composition of LPG used as an automotive fuel varies from almost pure propane to almost pure butane (Table 3). In the United States, the propane industry has attempted to adopt an automotive propane standard known as HD-5. Although proposed as long ago as 1967 (Kuivanen et al. 1967), the standard is still not universally observed. HD-5 requires a minimum propane content of 90% and a propylene content of less than 5% (volume basis). Propylene has low knock resistance. It does not occur in LPG obtained from natural gas processing plants but is found in the LPG resulting from petroleum refinery operations.

COMPARISON OF ENGINE USE CHARACTERISTICS

Several of the key defining characteristics of fuels with respect to use in internal combustion engines are listed in Table 4. As shown in Table 4, the volumetric air/fuel ratio for CNG is 9.6. One cubic meter of fuel is required for every 9.6 cubic meters of air charged. In other words, because the fuel gas must displace air, switching a gasoline engine to CNG results in a reduction of about 9.3% in the amount of air that enters the cylinder and a corresponding reduction in power (Figure 4). For propane, the gas displacement effect is only about 4.0%.

Both gaseous fuels have higher ignition temperatures and higher octane numbers than gasoline. The subject of octane number (index of resistance to engine knock) is somewhat murky for the gaseous fuels because the meaning of their octane number of more than 100 is not clear. An octane rating of 100 simply means that a fuel produces knock at the same compression ratio as when the engine is running on isooctane. Regardless of the technical problems in defining octane number for gaseous fuels, it is clear that methane should theoretically be usable at higher compression ratios (therefore higher efficiency) than gasoline, and that propane falls between the two. With respect to almost all defined fuel characteristics, values for propane lie between those for methane and gasoline. Thus there are many ways in which a two-fuel CNG/LPG system could be a more optimum design than a two-fuel CNG/gasoline system. For instance, the engine has to be designed to run on the fuel with the lowest octane number that it will see. This reduces the ability to achieve the highest performance when running on the fuel with the higher octane number. On LPG the engine can be optimized for a higher compression ratio than on gasoline, giving more power from the same engine displacement (Figure 5). Such an engine would then suffer less of a drop in performance when switching to CNG fuel. In other words, a CNG/LPG system can operate at closer to optimum efficiency for both fuels than can a CNG/gasoline system.



Source: Stokes 1993

Figure 3. Maximum allowable propane concentration

Table 3. LPG Composition (% by Volume) as Automotive Fuel in Europe

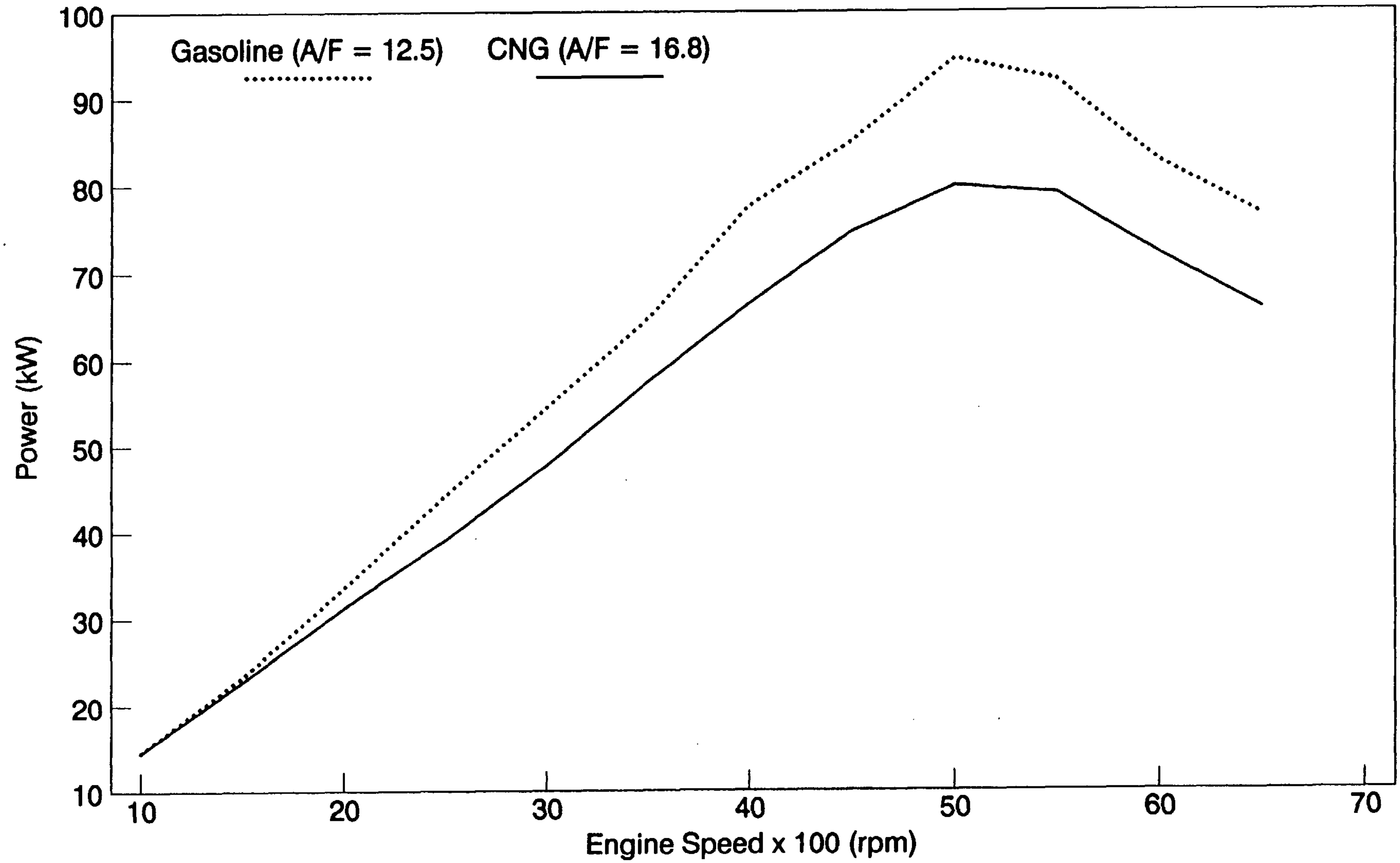
Country	Propane	Butane
Austria	50	50
Belgium	50	50
Denmark	50	50
France	35	65
Greece	20	80
Ireland	100	-
Italy	25	75
Netherlands	50	50
Spain	30	70
Sweden	95	5
United Kingdom	100	-
Germany	90	10

Source: Urban 1982

Table 4. Comparative Engine Use Characteristics

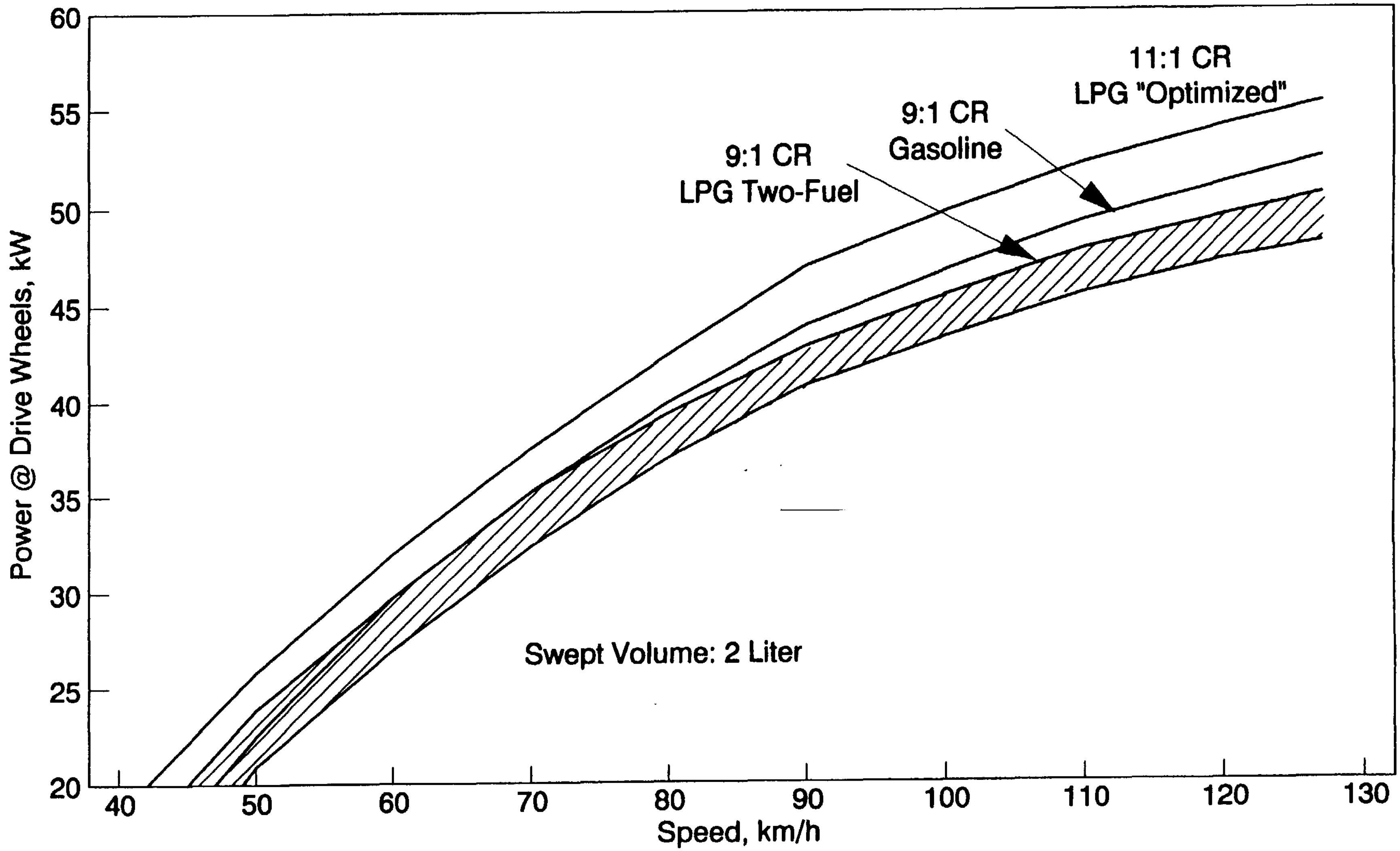
	Units	Methane	Propane	Gasoline
Autoignition Point	^{o}F	1,000-1,350	874	365
Autoignition Point	^{o}C	538-732	468-494	185
Flammability Limits	vol. percent	5-15	2.1-9.5	1.4-7.6
Stoichiometric A/F	kg/kg	17.3	15.7	14.7
Stoichiometric A/F	m^3/m^3	9.7	24.6	
Research Octane Number		130	112-125	91-95
Motor Octane Number		105	97-111	82-88
Wobbe Number	MJ/m^3	48.2	74.7	
Relative CO_2/Btu		0.76	0.92	1.0

Source: Various



Source: Yamamoto et al. 1994

Figure 4. Power of Honda engine on CNG and gasoline



Source: Frend 1981

Figure 5. Power output from gasoline, two-fuel LPG and dedicated high-compression LPG engines

Of particular importance in discussing gaseous fuels is the Wobbe number. The major gas pipelines control the Wobbe number of their delivered gas. However, different pipelines may control to different values of the Wobbe number. Variations in Wobbe number affect the power output and emission characteristics of gas-fueled vehicles. On engines equipped with orifice-based fuel/air mixing systems, the impact of Wobbe number changes will be similar to the effect of changing the equivalence ratio. Engines employing a lean-burn strategy for NO_x reduction will be particularly sensitive to changes in Wobbe number.

The volumetric heating values of the fuels, the volumetric air/fuel ratios, and the volumetric heating values of the stoichiometric air/fuel mixtures for several different gaseous fuels are shown in Table 5 and Figure 6. The last column of numbers in Table 5 reinforces the fact that the power obtainable from an engine is more a function of the amount of air that can be charged than of the heating value of the particular fuel being used. However, it does show that propane has an advantage over methane.

COMPARISON OF ENERGY STORAGE EFFICIENCY

The relative storage efficiencies, in both volumetric and weight terms, of CNG, LPG and gasoline are given in Table 6. Values given for CNG and LPG are based on pure methane and propane.

The first line in the table gives the ratio of the energy density of the fluids, under typical fuel tank conditions, to that of gasoline. In computing this number, the liquid density of saturated propane at 60°F was used, rather than the density at the normal boiling point. The latter value has sometimes been used in making comparisons found in the literature, but does not represent a real-life storage condition. For CNG calculations, a tank pressure of 3,600 psi was assumed.

Using the energy density ratios, a tank volume required to hold the energy equivalent of 20 gallons of gasoline (GGE) was calculated as shown in Line 2. LPG requires a 35% greater storage volume than gasoline and CNG requires 3.85 times as much storage volume as gasoline.

The weight of the tank required to contain the listed fuel volumes was then calculated. The weight of a gasoline tank was determined by actually weighing a tank that had been removed from a vehicle at a propane conversion center. The weights of propane and CNG tanks were obtained from vendors' product literature. In the case of CNG, it was assumed that four modular tanks were used. If available tank sizes did not match the desired capacity exactly, a weight was estimated for the desired capacity by taking the known weight for a known capacity and multiplying by the ratio of the capacities raised to the two-thirds power. This corrects for the fact that tank surface area increases with the square of a linear dimension while the volume increases as the cube of a linear dimension. For CNG, a wide variety of material choices are available at different weights and prices. A commonly used fiberglass-wrapped aluminum was chosen for this comparison.

Most tank volume comparisons found in the literature stop at this point. However, there is another correction that should be applied for gaseous fuels. This has to do with required ullage volume (vapor space left above the liquid level) in LPG tanks, and heel limits (material left in the tank after drawdown to the lowest practical level) in CNG tanks. LPG systems have some kind of safety fill-stop device to limit tank fills to no more than 80% to 85% of tank volume. This is to allow room for liquid expansion if the temperature rises after the tank is filled. Depending on the type of injector system used, CNG tanks may require a minimum tank pressure of about 150 psig. This could correspond to about 4% of original tank contents being unavailable.

Lines 5 and 6 in Table 6 list the necessary tank volumes and weights to contain 20 GGE when ullage and heel limits are factored in. The new effective energy density ratios and tank volume ratios are given in Lines 7 and 8.

Both methane and propane have a higher heat of combustion (the lower heating value, or net heating value is used for all comparisons) than gasoline, so less fuel weight is required to travel the same distance. Fuel weights are computed on Line 9. The bottom line in Table 6 gives the total weight of fuel plus tank for a fully loaded tank containing each of the three fuels. Although some penalty is involved in switching from gasoline to LPG, it is not significant, amounting to an increase of 65 pounds in vehicle weight with full fuel tanks.

Table 5. Volumetric Heating Value (LHV) of Fuel Gases and Energy Content of Stoichiometric Mixtures with Air

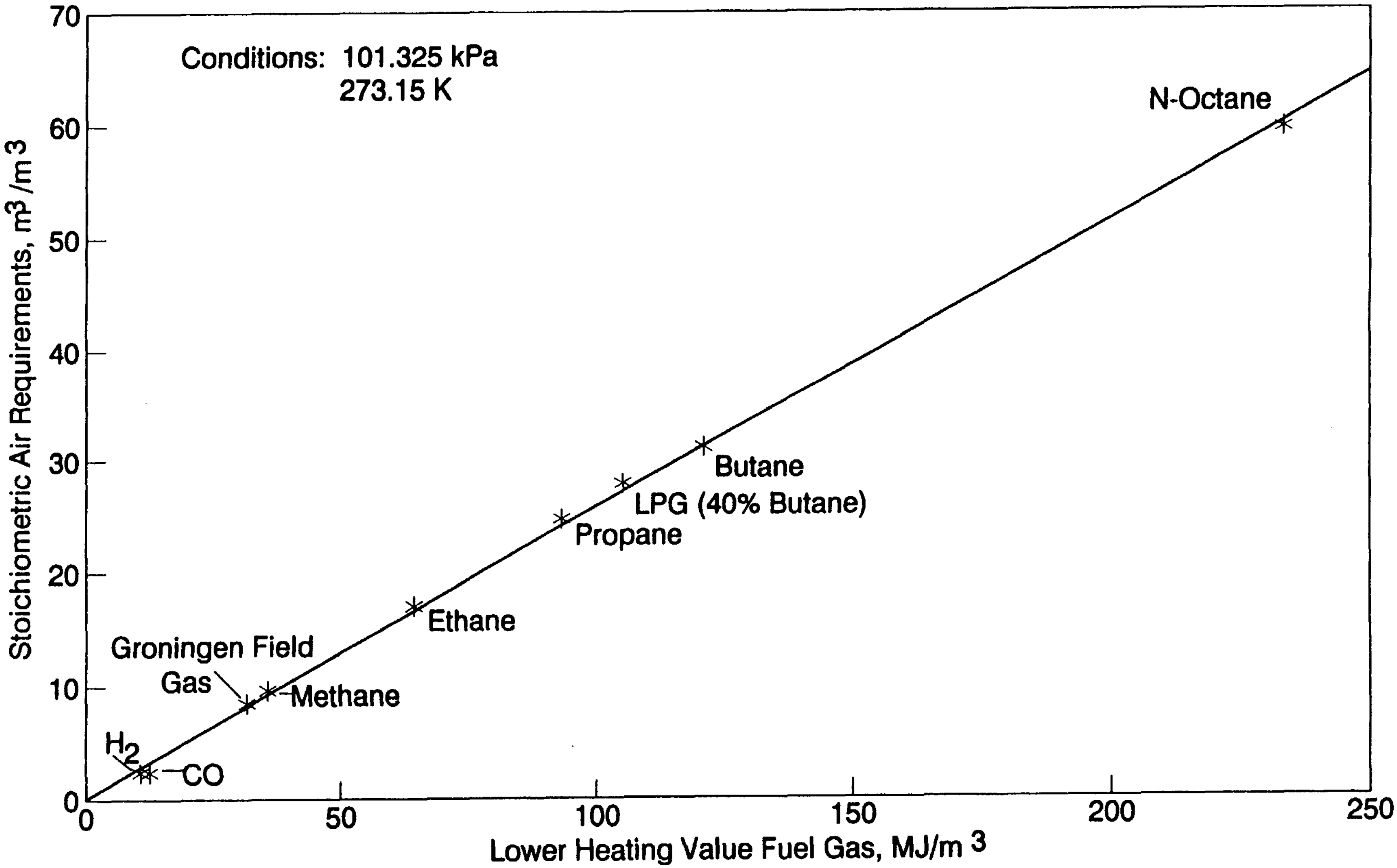
Fuel Gas	Calorific Value MJ/m^3	Air Requirement (m^3/m^3)	Energy Content (MJ/m^3)
Methane	35.9	9.67	3.36
Ethane	64.3	17.05	3.56
Propane	93.2	24.65	3.63
Butane	121.2	31.10	3.90
Natural Gas	31.7	8.53	3.32
LPG (40% Butane)	105.3	27.85	3.65
Hydrogen	10.8	2.41	3.16
Carbon Monoxide	12.6	2.41	3.70
Octane	233.3	59.50	3.92

Source: Klimstra 1986

Table 6. Comparison of Energy Storage Efficiency

	Units	CNG	LPG	Gasoline
1. Energy Density Ratio to Gasoline		0.26	0.74	1.0
2. Tank Volume for 20 GGE	gal	76.9	27.0	20
3. Tank Weight for 20 GGE	lb	530	89.0	25
4. Ullage and Heel Limits	percent	4	15	0
5. Corrected Tank Volume for 20 GGE	gal	80.0	31.8	20
6. Corrected Tank Weight, 20 GGE	lb	552*	99	25
7. Effective Energy Density Ratio		0.25	0.63	1.0
8. Effective Tank Volume Ratio		4.0	1.59	1.0
9. Weight of Fuel	lb	107	115	124
10. Full Tank Weight	lb	659	214	149

*4 tanks, each 20 gallons, aluminum/fiberglass
GGE = gallons of gasoline equivalent



Source: Klimstra 1986

Figure 6. Stoichiometric air requirements

COMPARISON OF VEHICLE EMISSIONS

The subject of emissions from alternative fuel vehicles has been covered extensively in the literature of the last few years. It was not the objective of this project to try to produce a definitive estimate of relative emissions. Rather, some general comparisons are presented, just to set the stage for making rough estimates of the benefits that could be achieved by the use of CNG/LPG vehicle systems.

Comparisons are hampered by the lack of good data for emissions from optimized LPG vehicles. Work under way at Chrysler Canada should remedy this problem in the future, but for now, the data available probably do not represent the best performance that could be achieved.

The following series of charts sheds light on various aspects of emissions from CNG and LPG vehicles compared to other types of vehicles. A recently reported comparison between propane and gasoline, using current technology, is given in Figure 7.

For both CNG and LPG, emissions of NO_x have generally been considered to be a problem, with most tests showing higher levels than from gasoline-fueled engines. However, Chrysler Corporation has tested a dedicated-CNG Dodge van against the California Ultra-Low Emission Vehicle (ULEV) standards with excellent results (Figure 8). This van used a special new three-way exhaust catalyst formulation. It may be presumed that an equally effective catalyst could be developed for LPG applications.

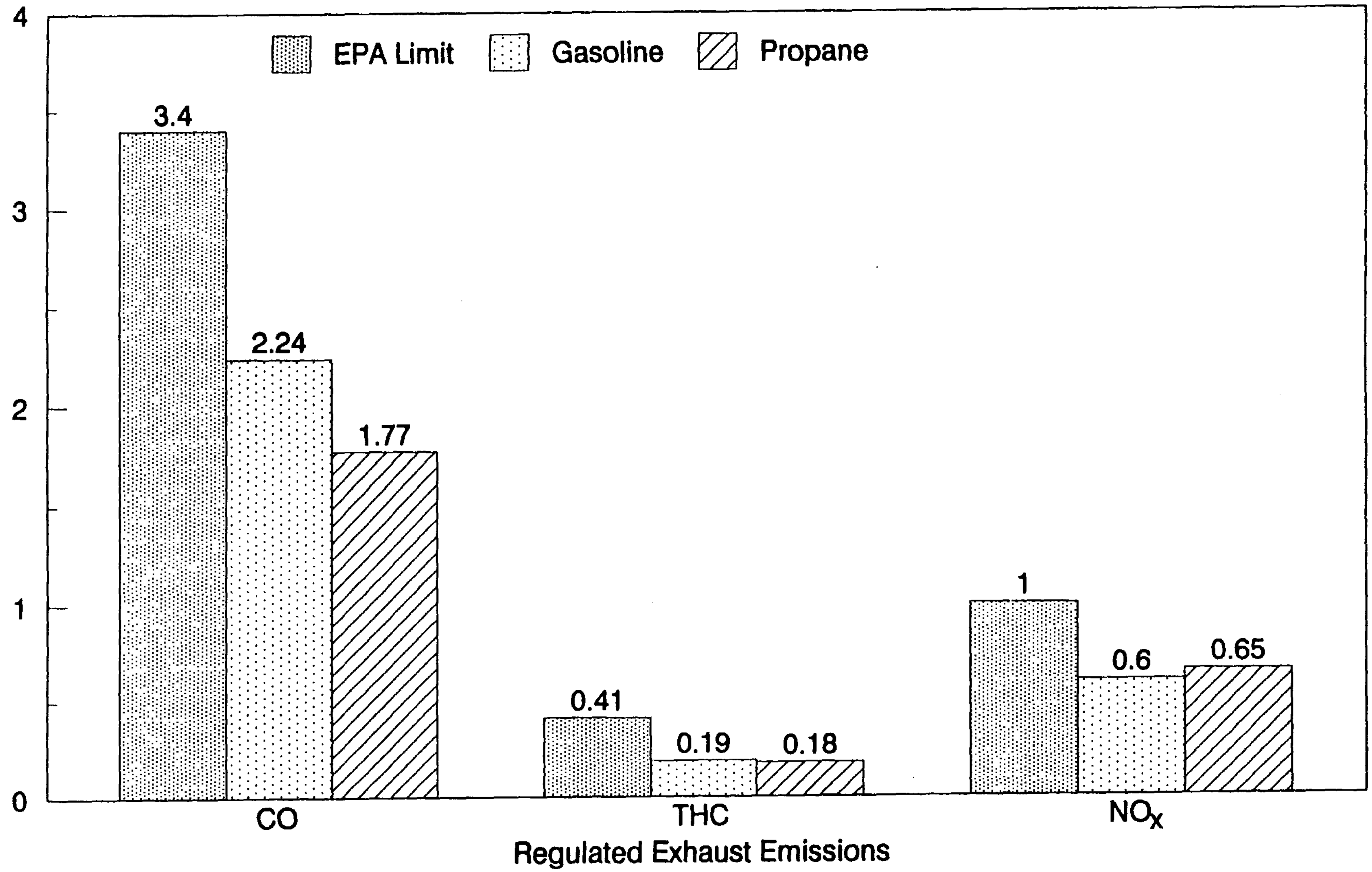
Figures 9, 10, and 11 give some comparisons from the literature showing carbon monoxide, non-methane organic gases, and nitrogen oxides, respectively, for a number of alternative fuels and gasoline. The crux of the emissions arguments presented in this report for using CNG/LPG instead of CNG/gasoline may be seen in Figures 12 and 13.

It is not sufficient to merely consider mass of exhaust emissions. One must also consider how hydrocarbon emissions and nitrogen oxides combine in the atmosphere to form smog. Smog-forming potential is estimated by calculating the atmospheric reactivities of each of the individual components in a vehicle's exhaust emission. Such calculations (Figure 12) show a clear-cut advantage for propane. Every gallon of gasoline that can be replaced by propane should cut typical exhaust ozone potential by almost one-half.

As noted in Figure 13, automobile exhaust emissions are being so successfully controlled that they now amount to only about half the total hydrocarbon emissions from a typical automobile. The other half comes from refueling, evaporative, and running losses. Propane fuel systems, being totally enclosed and pressure-tight, have none of these emissions. Therefore, a 50% reduction in overall emissions results just from fuel system characteristics.

GREENHOUSE GAS EMISSIONS

Calculations of greenhouse gas emissions from different fuels have been thoroughly reported, so that a summary of results here is probably redundant. Nevertheless, for the sake of completeness, Figure 14 presents the results published by Argonne National Laboratory. It can be seen that the best estimate for LPG gives it a more favorable ranking than gasoline, diesel fuel, methanol made from natural gas, compressed natural gas, liquefied natural gas, or ethanol made from corn. The reason LPG is preferred over CNG is that methane itself is a powerful greenhouse gas but propane is not.



Source: Phillips Petroleum 1994

Figure 7. Exhaust emissions of gasoline- and propane-fueled vehicles

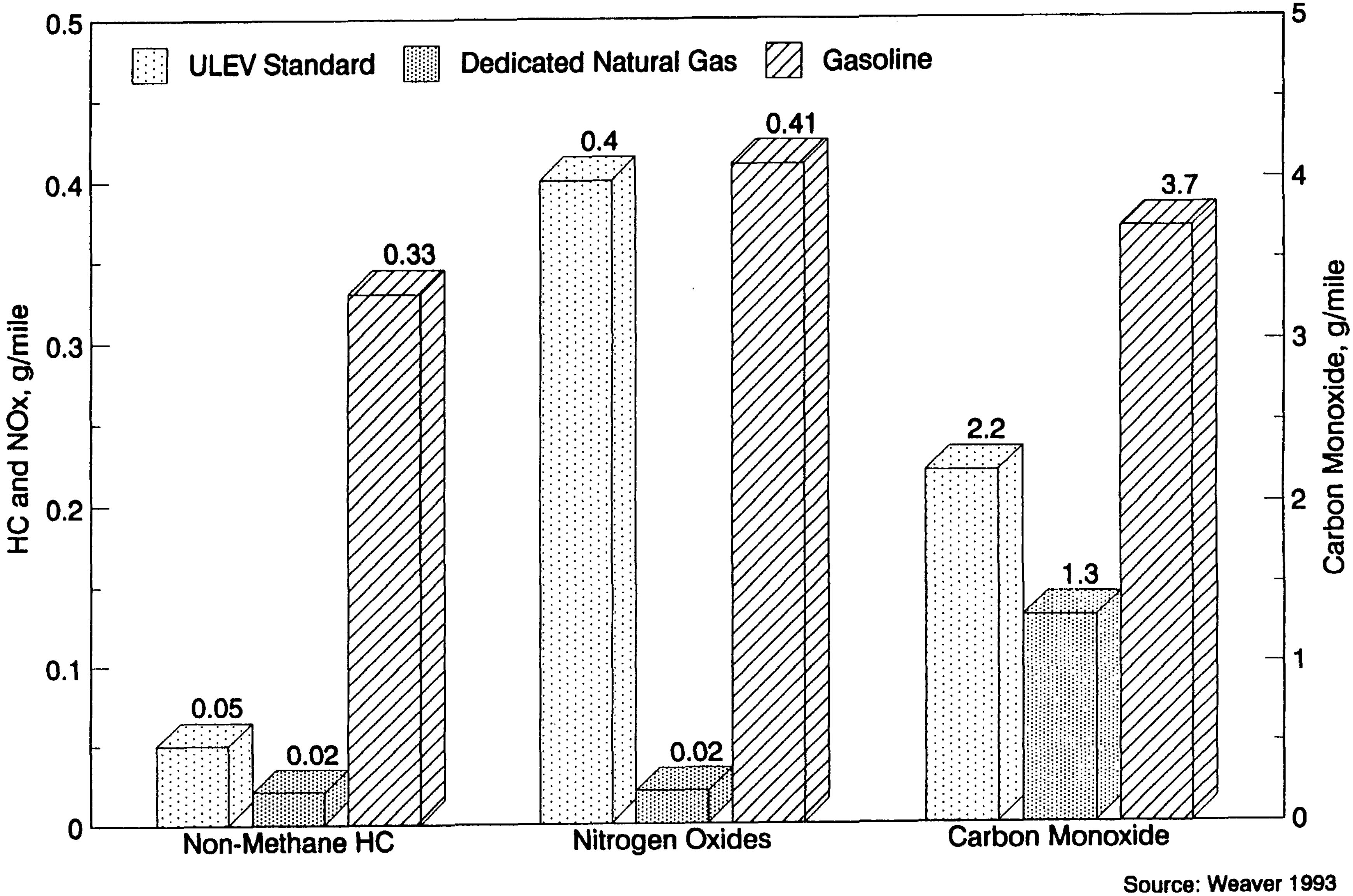
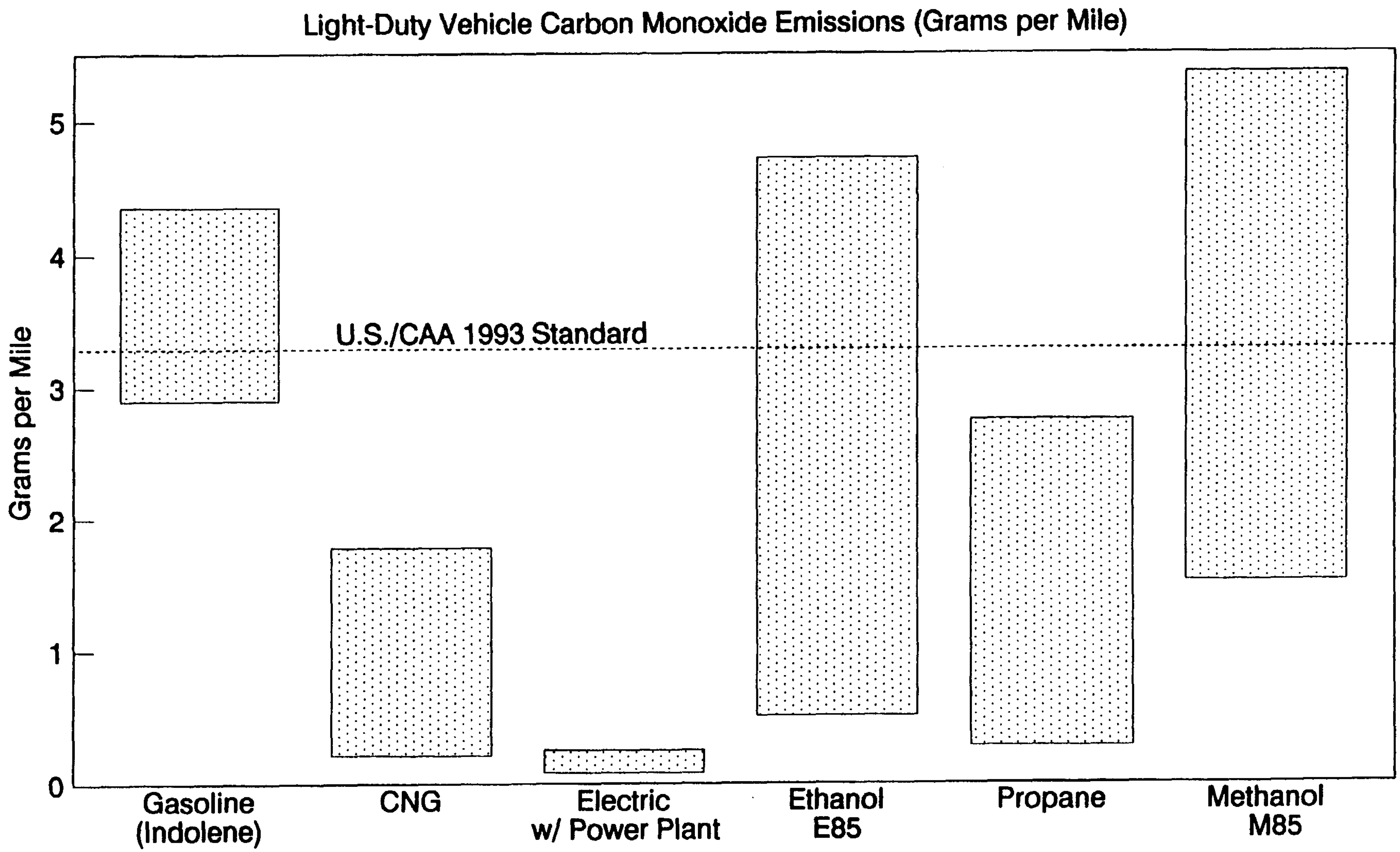


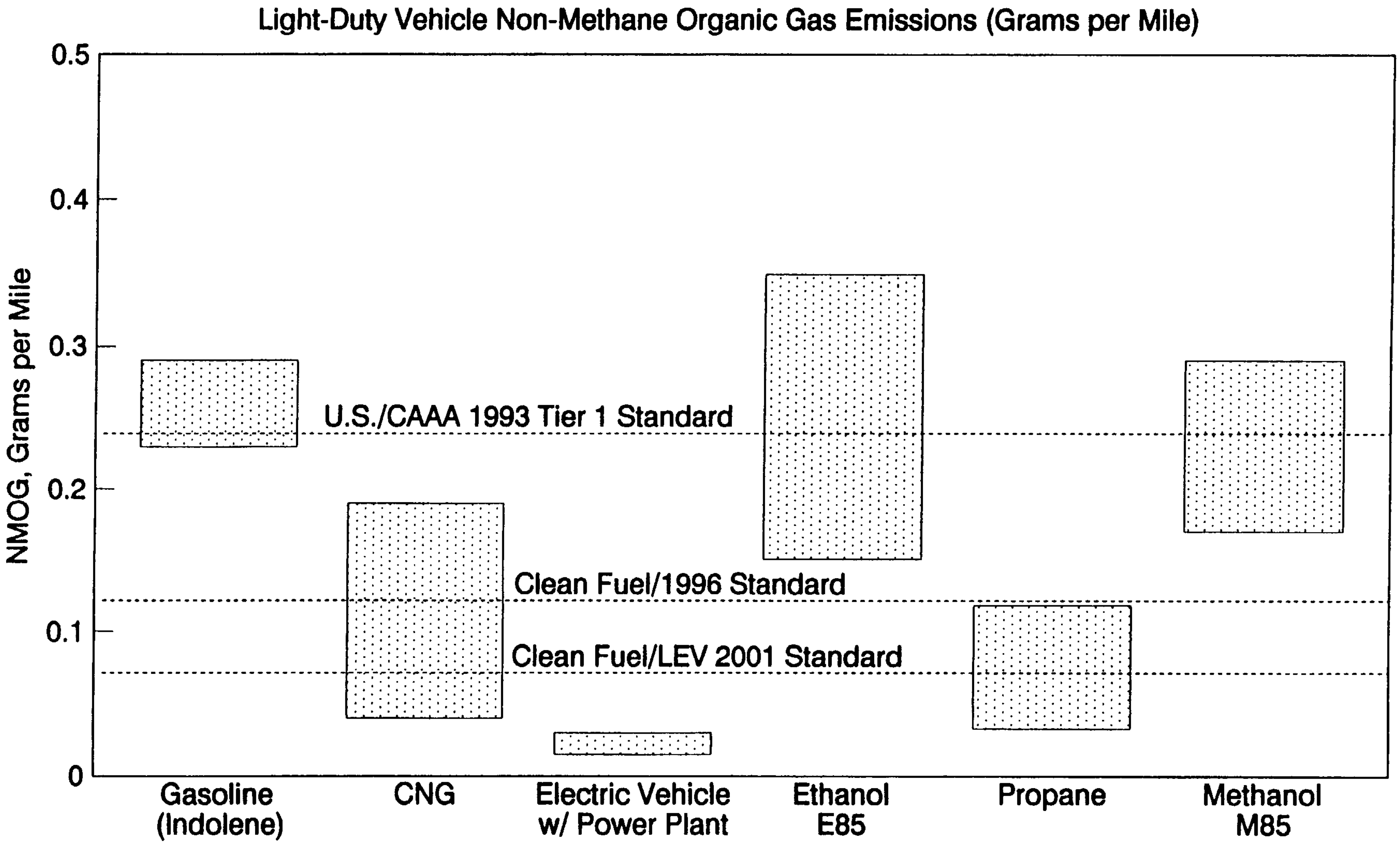
Figure 8. Dodge van emissions by fuel type



Note: Range of emissions reported from variety of sources (e.g., California Air Resources Board [CARB], General Motors [GM], The Environmental Protection Agency [EPA]

Source: Ohio Alternative Fuel Advisory Council 1993

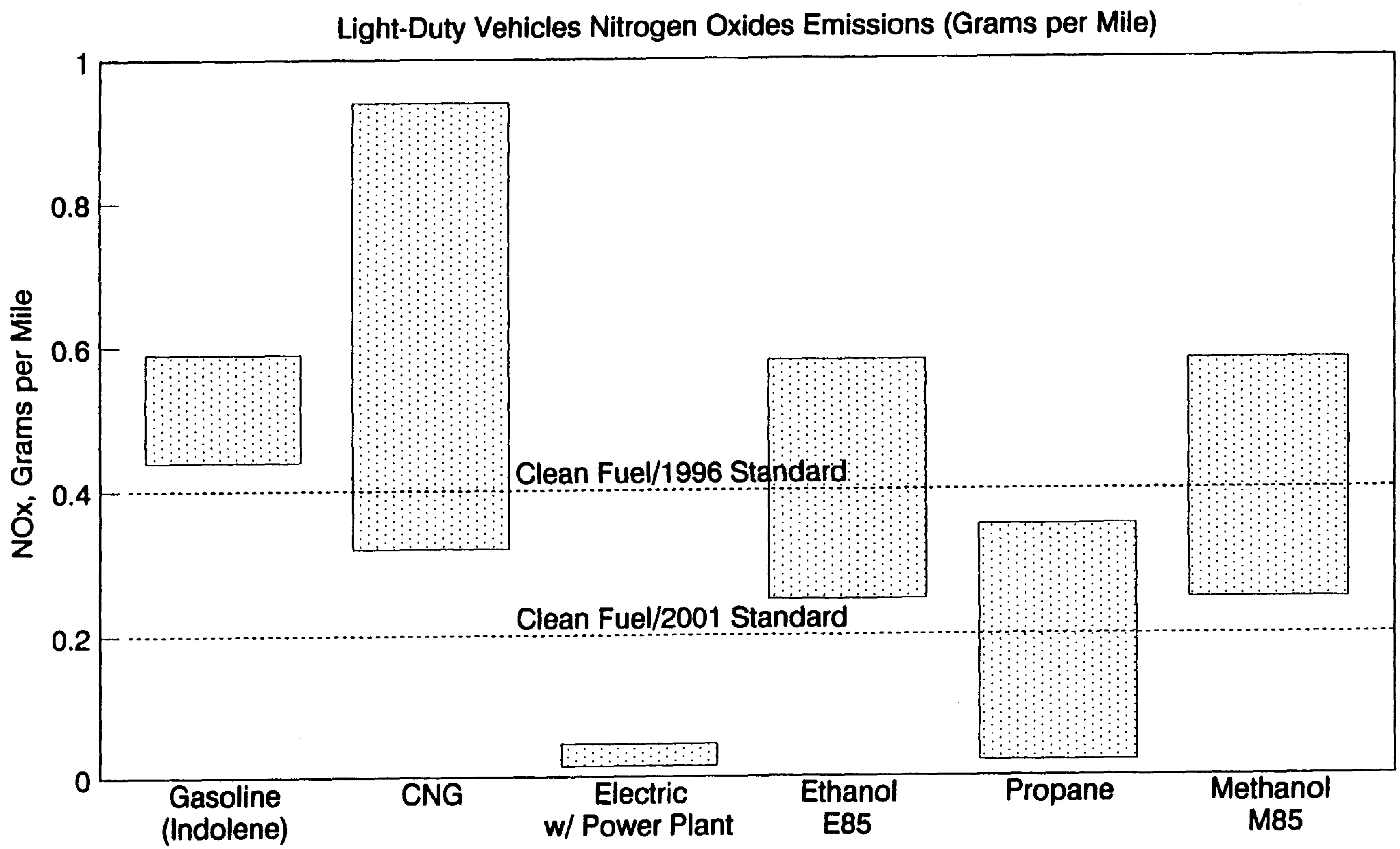
Figure 9. Range of recently reported emissions performance of alternative fuel vehicles



Note: Range of emissions reported from variety of sources (e.g., California Air Resources Board [CARB], General Motors [GM], The Environmental Protection Agency [EPA]

Source: Ohio Alternative Fuel Advisory Council 1993

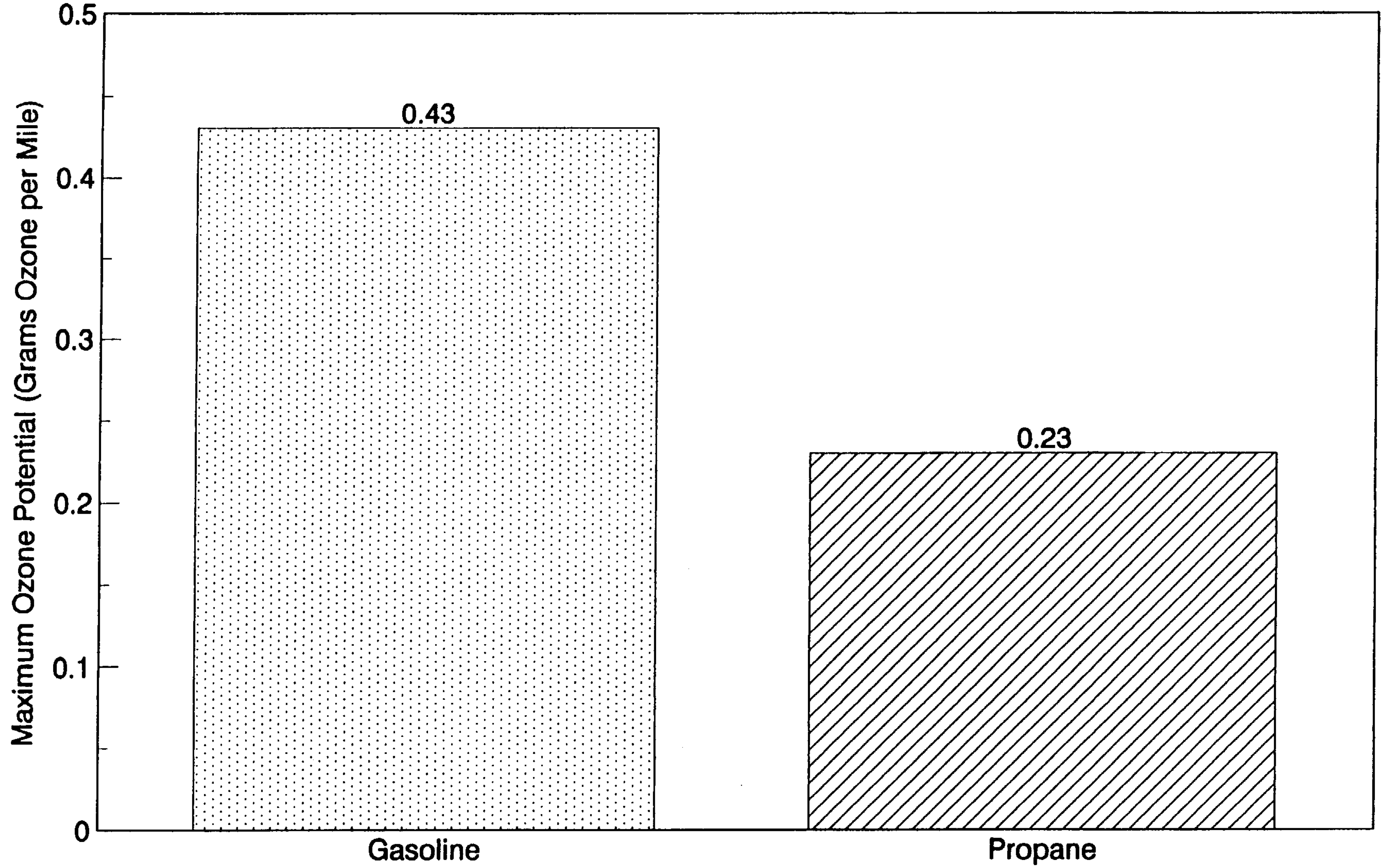
Figure 10. Range of recently reported emissions performance of alternative fuel vehicles



Note: Range of emissions reported from variety of sources (e.g., California Air Resources Board [CARB], General Motors [GM], The Environmental Protection Agency [EPA]

Source: Ohio Alternative Fuel Advisory Council 1993

Figure 11. Range of recently reported emissions performance of alternative fuel vehicles



Source: *Clean Fuels Report* 1994

Figure 12. Maximum ozone potential for gasoline and propane

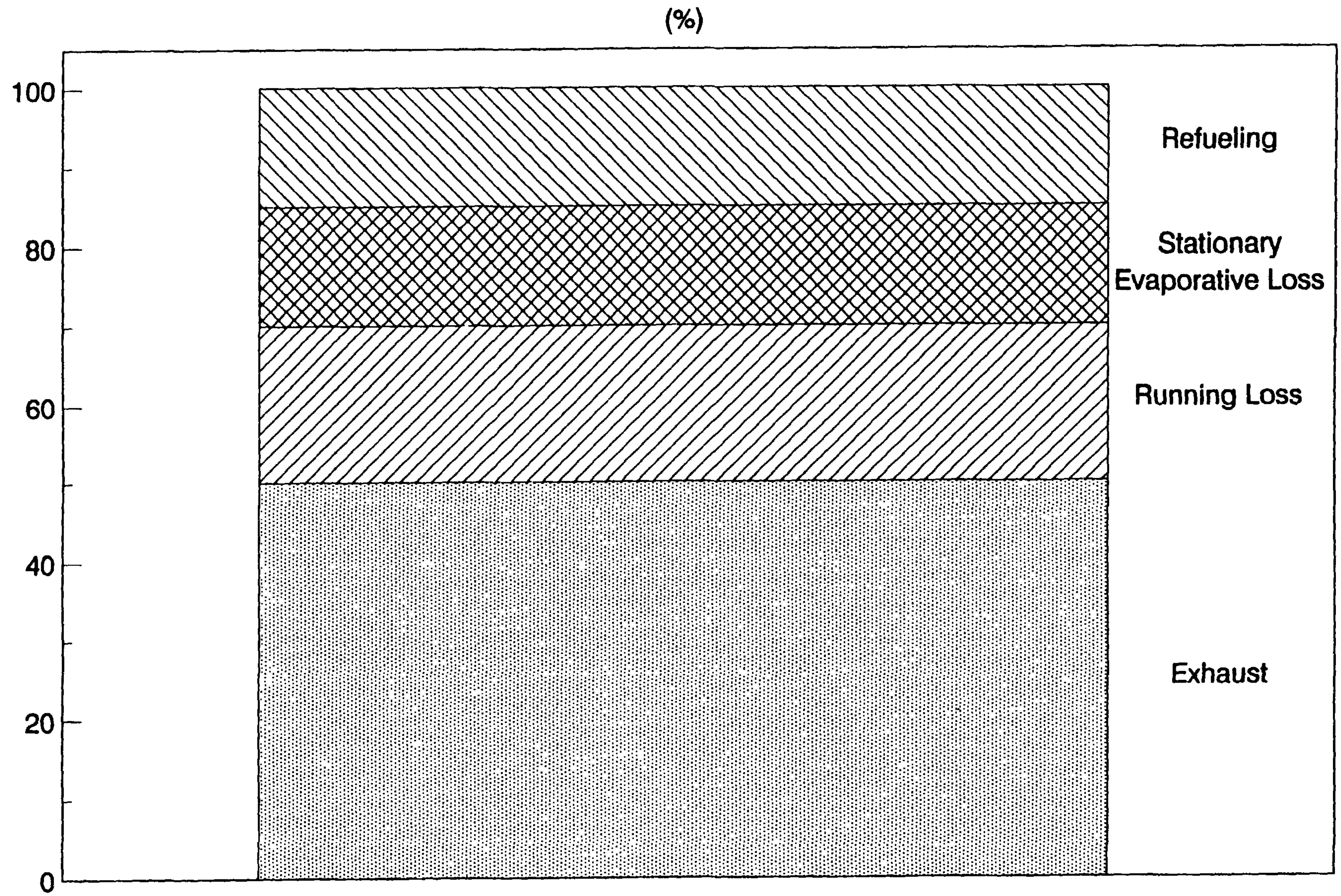
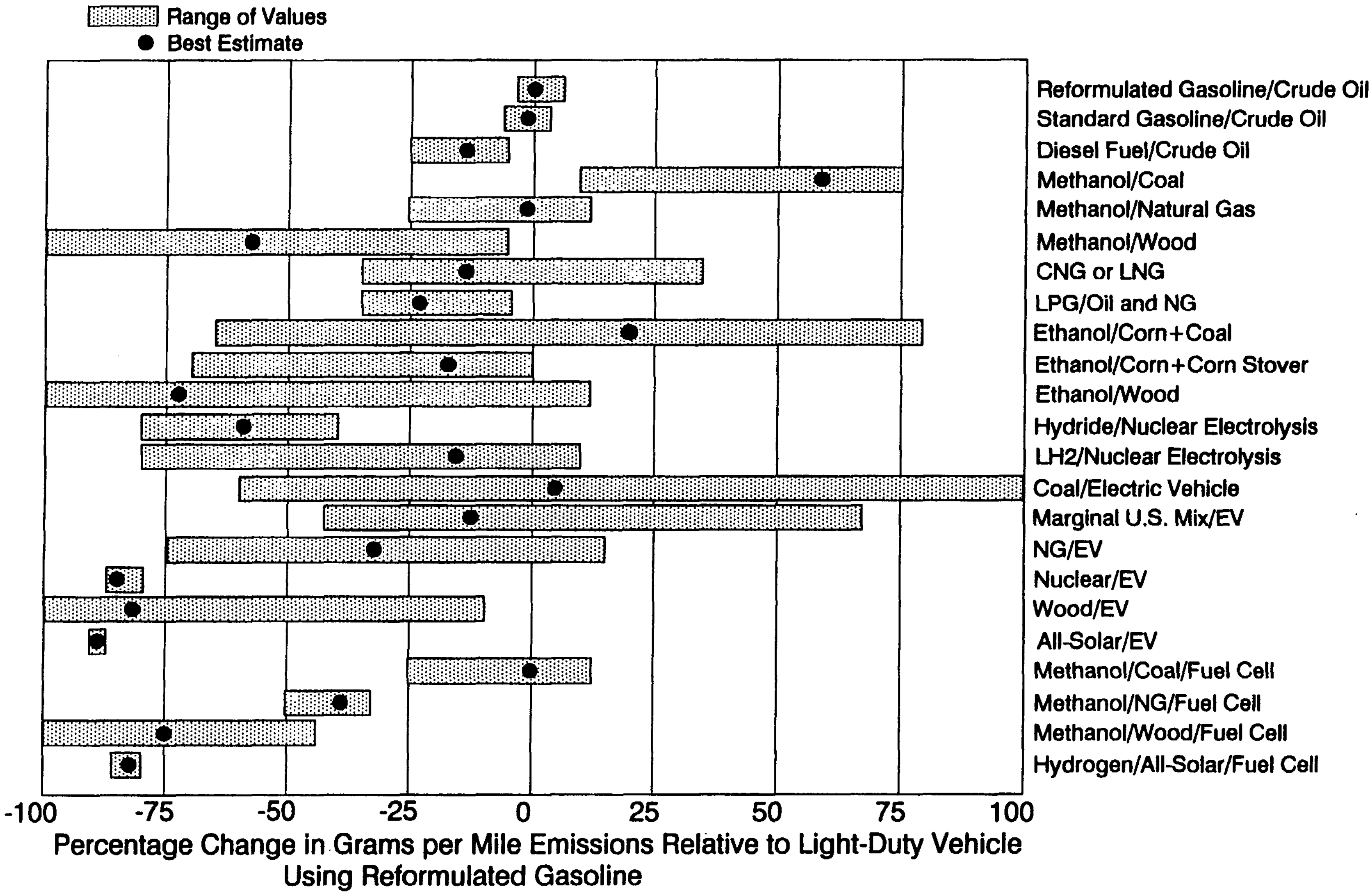


Figure 13. Hydrocarbon emissions from current gasoline vehicle



Source: DeLuchi 1991

Figure 14. Relative greenhouse gas emissions

CNG/LPG TWO-FUEL VEHICLES

DEFINITIONS

The terminology used to describe engines or vehicles that utilize more than one fuel has been confused in the literature. The U.S. EPA, in its proposed standards for emissions from gaseous vehicles (U.S. EPA 1992), defines dual-fuel as using either of two fuels, separately, one at a time. The term bi-fuel is defined as being associated with diesel engine conversions and referring to the use of gaseous fuel and diesel fuel simultaneously. Such an engine requires the use of at least some diesel fuel at all times. However, the word bi-fuel, in popular usage, appears to be most often referring to what EPA calls dual-fuel. In both cases, two separate fuel tanks are required. Similarly, popular usage of the word dual-fuel seems to be opposite to EPA's.

The word flex-fuel is universally used as referring to a vehicle that can use either of two fuels in a pure form or in any mixture of the two without any action on the part of the driver. Only one fuel tank is involved, and it can be filled with either fuel or a mixture at will.

In this report, the word flex-fuel is used in the same sense as it is defined above. In order to avoid confusion about what is meant by the words, bi-fuel and dual-fuel, we use a different term, two-fuel, to refer to a system involving two separate fuel tanks. Switching from one fuel to the other may be accomplished manually by the driver, or automatically in response to a low fuel level in one tank or in response to some other signal involving operating conditions.

The configuration in which two fuels are used simultaneously while drawing from two different fuel tanks is not considered in this work. Such systems generally involve adding an alternative fuel to the air stream entering a diesel engine--a process referred to technically as fumigation. There would not appear to be an application for such technology in the CNG/LPG systems that are the subject of this study.

TECHNOLOGY ASSESSMENT OF TWO-FUEL CNG/LPG VEHICLES

No technology issues involving two-fuel vehicles are more difficult than those for flex-fuel vehicles. In the most elementary two-fuel approach, there are simply two completely separate and distinct fuel systems. Each system consists of a tank, a flow regulator, and some means of coupling the flow regulator to the engine. A manual switch closes one set of fuel valves, opens the other, and makes any electronic connections necessary. Current CNG/gasoline and LPG/gasoline conversions to two-fuel operation are of this type. All current systems start with an engine designed for gasoline operation and then try to adapt it to operating as well as possible when using the other fuel.

There is no particular technical problem in putting two conversion systems on the same vehicle, making it a tri-fuel vehicle, and allowing the driver to switch from gasoline to CNG to LPG at will. Such a vehicle was exhibited by IMPCO Technologies, Inc. at the Texas Alternative Vehicle Fuels Market Fair and Symposium in 1993. Other instances of such tri-fuel vehicles have been reported as well.

Engine Control

With all two-fuel systems, it is technically impossible to optimize engine operations on both fuels. In the typical approach, a gasoline-optimized engine is made to run on CNG or LPG. It is not possible to increase the compression ratio in order to take full advantage of the high octane index of these fuels because the engine would then knock excessively when running on gasoline. Therefore, performance on CNG or LPG, on which the engine is expected to run most of the time, is less than desirable. Typical results were shown in Figure 4. The use of CNG led to a 12% power reduction and a 13% reduction in torque at wide open throttle.

The alternative approach has been explored experimentally, in which an engine is optimized to run on CNG, and given only a "limp-home" capability on gasoline (van der Weide 1994). In the experiments, the engine was partially optimized for CNG operation (11.5 compression ratio). If gasoline operation became necessary, a fixed engine calibration went into effect. In order to compensate for the lower octane level of gasoline, the air/fuel ratio at high loads was controlled to a rich mixture (open-loop) to prevent detonation and to keep the catalyst temperature below certain limits.

Exactly the same situation, but in different degrees, would prevail in considering a two-fuel CNG/LPG system. LPG has a higher octane index than gasoline, so the tradeoffs can be more favorable--but it is not possible to operate current engines at conditions that are optimum for both LPG and CNG. Operation on one fuel or the other, or both, must be at less than optimum conditions.

Modern automobile engines are usually operated near the stoichiometric air/fuel ratio with an oxygen sensor in the exhaust gas providing the control signal for a "closed-loop" or feedback control scheme. Theoretically such a control system should be insensitive to the fuel burned. Regardless of fuel composition, monitoring the oxygen content in the exhaust should make it possible to maintain the engine air/fuel ratio at stoichiometric. Natural gas exhaust creates some bias in the oxygen sensor, which has to be accounted for by the engine control computer. Any differential oxygen sensor bias between CNG and LPG could be handled by the engine control algorithm. When the fuel switch tells the computer that the fuel is being changed, the computer switches over to the proper control algorithm, using the correct oxygen sensor bias and the correct curve for spark timing versus engine speed or whatever other control scheme is used. There should be no technical difference between designing a two-fuel CNG/LPG control system and a two-fuel CNG/gasoline or LPG/gasoline system.

Although air/fuel control systems based on an oxygen sensor in the exhaust can keep an engine supplied with a correct stoichiometric mixture, it cannot account for changing combustion properties. When fuel composition varies over a wide range, a resulting change in combustion velocity can result in destructive engine knock. This can be counteracted over a certain range by the use of knock sensors that change the spark timing.

If a lean-burn engine strategy is used instead of stoichiometric operation, the engine control issues become more complex, because oxygen level in the exhaust gas is no longer the control parameter.

Fuel Metering

Because both fuels are gaseous, a common fuel metering approach can be used, unlike the two-fuel systems involving gasoline (or any other liquid fuel) and a gaseous fuel. It might be thought, therefore, that a simple fuel metering system could be used, just connecting it alternately to either the CNG tank or the LPG tank. This is not possible, however, with most of the conversion systems now on the market. This is because of the large differences in fuel tank pressure and vapor energy density.

The GFI Control Systems, Inc. (GFI) gaseous fuel injector for LPG is similar in size to that for CNG but the LPG version requires an additional orifice because of the lower pressure drop available. In the GFI throttle body injection system, a set of five sonic metering orifices are used. Each orifice is twice as large as the proceeding one. The NGV pressure regulator is a single-stage system with an output of 30 to 100 psig, whereas the LPG system uses a two-stage regulator with an output of 3 psig (Carter 1988).

The GFI conversion system includes a new engine control module (computer) that essentially usurps the Original Equipment Manufacturer (OEM) engine computer but ties into it electronically and feeds it enough signals to keep it functional. The GFI system includes its own sensor network and uses only the oxygen sensor from the OEM system. The LPG and CNG computers are physically identical; only the software is different. A different "engine map" is required for each case.

The GFI computer controls fuel flow, spark angle, and dashboard fuel gauge. It can be set to work open-loop or closed-loop, lean-burn or stoichiometric, with or without exhaust gas recirculation, with or without a catalyst, and with or without turbocharging or supercharging.

IMPCO offers a gaseous fuel metering system that is port injection, with sequential injection. Each injector is a single orifice and the injection process is pulse-width modulated. The same injector could be used for both LPG and CNG if wide enough pulse-width variation could be obtained. To get accuracy at small pulse widths, an injector valve with rapid and repeatable opening time is required. Currently, that may be possible only with very expensive electromagnetic injector valves. For instance, the Lucas injector valve with 0.7-millisecond opening time that is used in two-cycle diesel engine conversions costs $1,800.

IMPCO intends to produce a system that is identical, with respect to materials, for both CNG and LPG. Again, a different engine map would be required for the two fuels, but this is already being done for gasoline/LPG two-fuel conversions, so the technology is no different, only the software.

In sum, there is no technical problem with a two-fuel CNG/LPG vehicle that would be worse than with current two-fuel CNG/gasoline or LPG/gasoline systems. In many respects, the problems would be lesser in magnitude because of lesser differences between the fuels, but in no case do the problems seem to disappear completely. A truly universal CNG/LPG pressure-regulator-injector system with advanced electronic control characteristics should be technically possible, but is not yet on the market.

COST ASSESSMENT

When considered from an OEM standpoint, there should be no large basic differences in cost between a two-fuel CNG/LPG system and a two-fuel CNG/gasoline or LPG/gasoline system. Every case requires separate tanks, separate fuel injection systems, and separate engine maps in the computer control module. A single gaseous fuel injector system that could handle both CNG and LPG would make that part of the system less expensive than for a two-fuel CNG or LPG system with gasoline. Because LPG tanks are larger and more expensive than gasoline tanks to provide the same range, the CNG/LPG tank systems will be somewhat more expensive.

TECHNOLOGY ASSESSMENT

Gas Composition Sensor

The concept of a flex-fuel CNG/LPG vehicle is based on a vehicle tank that could accept either CNG or LPG at pressures up to those normally used in CNG systems (say 3,600 psi). A fuel metering system and engine control module would be able to accept any range of composition of CNG/LPG mixtures and modify the fuel injection rate and timing, spark timing, etc., to optimize engine operation accordingly.

Optimizing such a system would require a gas composition sensor. There are different physical principles on which such a sensor could be based, such as infrared absorption, thermal conductivity, and refractive index. The Gas Research Institute (GRI) is currently sponsoring research into techniques for measuring natural gas composition in a vehicle fuel system. Because LPG is a naturally occurring component of natural gas, it is likely that whatever sensor system is developed for CNG could probably be extended to mixtures of CNG and LPG. Although the natural gas industry has developed an energy meter for natural gas pipeline accounting (Anon. March 1994), the meter is based on combustion principles, is bulky and expensive, and is not at all suited to vehicle applications. Recent work at BKM Inc. (Beck et al. 1993) has focused on the development of a sensor to compute the hydrogen/carbon ratio of gaseous fuels based on measurement of the speed of sound in the gas.

Fuel Metering

The technical issues involving a flex-fuel injector for CNG/LPG are basically the same as those discussed earlier for a two-fuel CNG/LPG system. A single injector that can handle either CNG or LPG alone in a two-fuel system would probably be capable of handling their mixtures as well.

Engine Control System

Once the composition of gas flowing to an engine has been sensed, there must be a way for the engine computer to change settings in response to a composition change. The current system for stoichiometric engines consists of a look-up table in the engine control computer. Such a system can probably handle no more than about a 15% change in fuel composition. Greater changes will require a more versatile strategy.

Variations in gas composition in a stoichiometric, naturally aspirated engine are readily compensated for by closed-loop oxygen sensors and controls. On the other hand, lean-burn turbocharged engines operating near the lean misfire limits require a different control strategy. A typical digital, multi-point, sequential gas engine fuel management system performs its function by controlling:

- Fuel quantity per injection
- Fuel injection timing
- Ignition timing
- Air quantity per cylinder, per cycle.

Beck et al. (1993) describe how, for example, such a system could react to a step change from methane to propane. It would command the engine to make the following changes:

- Retard ignition timing 6 to 12 degrees
- Reduce maximum fuel per cycle by 20% to 30%
- Increase lambda incrementally by 0.1 to 0.2 units of excess air ratio.

To actually optimize the operation of a lean-burn engine running on either fuel, a more complex engine control strategy would be needed. Franklin et al. (1994) describe a two-dimensional optimization process that simultaneously adjusts the spark timing and air/fuel ratio of a lean-burn natural-gas-fueled engine. This was done by first mapping the thermal efficiency against spark timing and equivalence ratio at a single speed and load combination to obtain the three-dimensional surface of efficiency versus the other two variables. An adaptive control strategy is then based on introducing small disturbances into the timing (dithering the timing) and detecting the corresponding changes in engine speed. The basic control logic is designed to find the timing that corresponds to maximum brake torque.

The air/fuel ratio can also be controlled in a manner similar to the timing. The air/fuel ratio can be dithered and the engine response determined. To achieve the air/fuel ratio that gives maximum fuel economy, the air flow must be dithered with a constant fuel flow. On the other hand, the air/fuel ratio for maximum power can be determined by dithering the fuel flow at constant air flow. The dithering is superimposed on top of changes in air/fuel ratio associated with normal engine operation.

The optimum values of timing and air/fuel ratio for a lean-burn engine are interdependent. Therefore, it is desirable to optimize timing and air/fuel ratio simultaneously. To do this, a control strategy that varies both parameters during each dither cycle and determines appropriate corrections for each must be used. In this manner, the timing and air/fuel ratio will follow a path to their optimum values. It seems reasonable that such a control strategy could handle a shift in composition between methane and propane.

LPG Vaporizer

Another difference between CNG and LPG systems is that LPG systems require a vaporizer. (Different groups are working on a liquid injection system for LPG, but such a system would not be applicable to CNG, so we do not discuss it under the flex-fuel CNG/LPG concept.) It is necessary that LPG fuel systems draw from the bottom of the tank rather than the top. If engine feed were drawn from the gas phase, the heavier, higher boiling components in LPG would gradually become concentrated in the liquid phase, creating a liquid mass with a low vapor pressure and a high freezing point. This liquid would create various problems in the fuel feed system. Therefore, LPG systems draw from the bottom of the tank and send the liquid through a vaporizer that is heated by engine coolant.

Although CNG could be sent through the vaporizer, heating the CNG would decrease engine power (as the temperature of the gas increases, its density decreases and less mass can be charged to the piston). Therefore, a vaporizer heat control system would be necessary to make sure that heat is added to the fuel stream only when liquid LPG is present.

A flex-fuel system in which LPG is intended to be the reserve fuel would require a fuel management scheme in which fuel was drawn from the top of the tank first. After pressure was reduced to a specified level, the draw-off point would be switched to the bottom of the tank. Then heat input to the vaporizer would be increased.

One potential problem that may require study is the possibility of condensation of liquid in the pressure regulator when a mixture of methane and propane is passing through it. Condensation could occur by two mechanisms. Normal partial condensation of propane could occur because of cooling of the gas stream during pressure reduction. Retrograde condensation (see later discussion of this phenomenon) could occur even at constant temperature in mixtures that are near their critical point. Once the possible conditions for condensation are mapped, a sophisticated strategy for heat control to the vaporizer should be able to prevent such condensation from actually occurring.

Exhaust Catalyst

To date, an efficient catalyst for methane in engine exhaust has not been developed. Of course, this is a problem for CNG/gasoline two-fuel systems as well as it would be for CNG/LPG systems, either two-fuel or flex-fuel. It would seem to be easier to develop a catalyst that works well with both CNG and LPG than it is to develop one that works well with both CNG and gasoline, but this is only speculation.

Fuel Tank Management

The most uncertain aspect of a flex-fuel CNG/LPG system involves the fuel tank management system. When the concept was first proposed, it was speculated that propane could perhaps serve as a sort of storage medium. If some amount of liquid propane were placed in a tank first, methane could then be added to the tank and a certain amount would dissolve in the liquid. Then, as vapor phase material were drawn off to supply the engine, methane would bubble out of the liquid, leaving most of the original propane in place to act as the reserve fuel. A brief examination of the thermodynamic properties of methane/propane mixtures reveals this concept to be impractical.

Mixtures of methane and propane do not form two-phase systems at temperatures and pressures above about 45°F and 1,500 psi. Thus, if one starts with a tank containing liquid propane (below a specific critical mass that is a function of temperature) and begins adding methane, a point is reached where the liquid interface disappears and a single-phase system of uniform composition develops. Withdrawing material from any point in this tank will yield a mixture of methane and propane of the same composition ratio as the relative total mass of each compound that was added to the tank. It is not possible to withdraw a feed rich in methane by drawing from the top of the tank nor to withdraw a feed rich in propane by drawing from the bottom of the tank. Thus the concept of adding natural gas to the vapor space "on top of" a mass of liquid propane is not achievable.

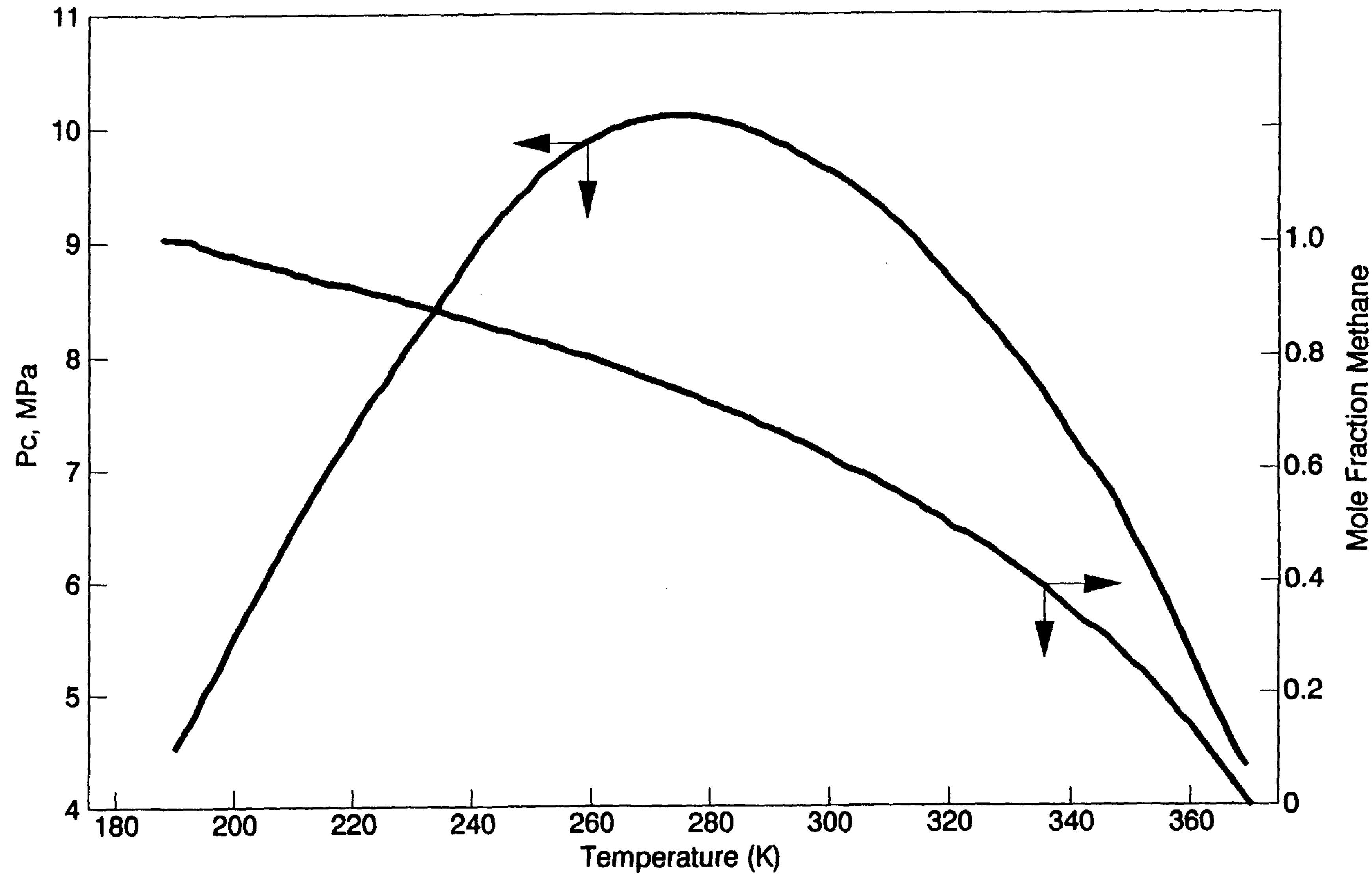
The critical properties of the methane/propane system are shown in Figure 15. The uppermost curve is the "critical curve," or the locus of critical points for the methane/propane system. It represents the locus of points on the boundary of the two-phase region at which the composition of the vapor and liquid phases become equal. If a mixture with the approximate composition given by the lower curve is present, and either the temperature or the pressure is increased further, a single, homogeneous phase will be formed.

Near the critical curve, the phenomenon of retrograde condensation may occur. This is the term applied when a mixture whose composition lies between that of the critical point and the cricondentherm point (the maximum temperature at which any vapor can be condensed) is isothermally compressed. First, as the dew point is reached, some liquid is condensed; as compression continues, the amount of liquid first increases, then passes through a maximum and decreases, and finally disappears altogether at higher pressures.

The design of a fuel tank system to accept either CNG or LPG represents a number of challenges. Because CNG systems operate at a much higher pressure, a CNG tank should be safe for LPG applications, as far as pressure ratings are concerned. However, LPG systems normally limit the liquid level to 80% to 85% of total tank volume. Older systems do this by using a "spitter valve." This is simply a valved-off dip tube, with the bottom of the tube at the 80% level. During tank filling, the valve is opened and allowed to vent to the atmosphere. When the liquid level reaches the dip tube, surges of boiling liquid begin "spitting" from the valve, alerting the attendant to terminate the filling procedure. Modern systems use a float or other liquid level gauge (electro-optical level detectors are available) to avoid venting propane through a spitter valve (Rice 1986).

A spitter valve would obviously be incompatible with a CNG/LPG tank that could be under as much as 4,000 pounds of pressure. And even presuming that a float could be devised to withstand that pressure, there would be no liquid interface for it to float on when the system entered the single-phase region. Similarly, there would be no interface for an electro-optical system to detect. Thus, there seems to be no way of using such techniques to limit the propane fill once the single-phase region is reached. In other words, if a tank contained 1,500 psi of methane to begin with, and propane were added slowly or with agitation, there would never be a liquid interface to detect, regardless of the final pressure reached.

One may then question whether there is any need to limit the propane fill at these conditions other than by pressure. The answer is probably not, but one must calculate the compressibility of the mixtures, to see whether a given temperature rise after filling would cause a greater pressure increase than expected in the case of methane alone.



Source: Miller et al. 1980

Figure 15. Critical properties of the methane/propane system

However, if one starts with less than the critical mass of methane in the system and adds propane at low temperatures, it is possible to end up with a tank mostly full of liquid at high pressure. An increase in ambient temperature could then result in high pressures because of liquid expansion. Thus, some method must be provided for limiting the maximum propane fill when little or no methane is present. The float system seems impractical because the operator would never know whether lack of a float signal meant an under-filled tank or just that the contents were in the single-phase region. It would be difficult to incorporate an understanding of the critical-point thermodynamics of binary systems into operating manuals for the average vehicle owner/operator.

One potential scheme that seems technically feasible would be to designate only one tank of a typical multi-tank CNG system as the propane receptacle. The top of this tank would be connected to the other tanks via a small-diameter fuel line. Such a line would act as a diffusion barrier, preventing large-scale mixing between the tanks, but allowing for liquid expansion in the propane tank should it become over-filled. A fuel composition sensor in this line could provide the shut-off signal for propane refueling. A careful study of potential vapor-space compositions would be necessary to decide on the composition levels that should be used to trigger a shut-off signal.

A concept that could hold promise for the CNG/LPG system is the "tank within a tank" design demonstrated in The Netherlands (Westerside and Syke 1980). The design principle is that a second tank is constructed inside the main tank with a size equivalent to 20% of the main tank capacity. This inner tank is fitted with two very small holes, one at the top and one at the bottom. The holes are so small that liquid can flow through only very slowly. Thus the 80% space of the main tank can be filled completely with liquid and very little will enter the small tank during the refueling procedure. However, if the tank temperature later increases, the liquid can expand slowly into the smaller tank to relieve the buildup in hydraulic pressure.

Refueling System

Any flex-fuel CNG/LPG refueling system would require high-pressure liquid propane pumps, capable of filling a vehicle fuel tank at pressures up to 3,600 pounds. Liquid pumps capable of such high output pressures are not unreasonably expensive. Gear pumps with the required output can be obtained for a few hundred dollars. By putting the pump and a check valve downstream from the retail fuel dispensing system, relatively few changes would be needed. Only the lines and valves from the pump to the vehicle would have to be high pressure.

Optimization of Fuel Composition

Examination of Figure 15 shows that large amounts of methane can be dissolved in liquid propane in the region near the critical point. For example, at approximately 300 K and 6.8 MPa, it is possible to produce a liquid with a composition of more than 60 mole percent methane content. This suggests another fueling concept--the sale of CNG/LPG blends tailored to give different results. A service station selling both CNG and propane could create a dispenser that mixes the two together in a specific ratio as the vehicle tank is filled. Many variations on this concept would be possible for an individual fleet operator. The filling procedure could be programmed to achieve different goals according to a particular vehicle's mission, such as:

- Greatest range (all propane)
- Least cost per unit of fuel (probably all CNG)
- Least cost while guaranteeing a specific range
- Least cost for a round trip with on-the-road refueling of one fuel or the other.

The Super-Fuel Concept

The problems involved with fuel tank management and engine control for a true flex-fuel CNG/LPG system suggest a potentially useful alternative approach that will be referred to as the super-fuel concept. The idea behind this concept is that instead of trying to make engine and fuel systems adapt to a new fuel, perhaps we should focus on changing the characteristics of the fuel itself to get the desired change in performance. This was the approach followed, for example, in Brazil in 1990 when a shortage of ethanol fuel developed (Branco and Szwarc 1993). It was desired to increase the amount of fuel available by beginning to use methanol. But rather than attempt to adapt or produce engines to run on methanol, a blend was developed, consisting of 33% methanol, 60% ethanol and 7% gasoline. This blend could be run in existing engines designed for neat ethanol fuel.

Similarly, we are concerned here with the shortcomings of natural gas with respect to vehicle range. Rather than attempting to come up with systems that can run on either CNG or LPG, perhaps we should consider modifying the composition of CNG to achieve the desired effect. This will be referred to as the super-fuel concept.

Super-fuel, for the purposes of discussion, is a blend of methane and propane. It is envisioned as being produced at the refueling station. CNG and propane would be metered into the vehicle simultaneously through a single line, at a fixed ratio. By proper choice of the composition ratio, it is possible that a system with the following characteristics and advantages would result:

- Up to a 40% increase in vehicle range compared to CNG
- No possibility of over-filling tanks with liquid, so liquid level controls not necessary
- Fuel composition varies only through a relatively narrow range
- Only one injector and one engine control map needed
- Engine can have compression ratio optimized for the mixture composition.

The super-fuel concept arises from a consideration of the following factors:

- The energy density of gaseous propane is almost three times that of methane (2,517 versus 1,010 Btu per cubic foot at 60°F and 14.7 psia).

- Methane and propane are mutually soluble.

- In a tank containing a mixture at a temperature above the cricondentherm, no liquid can be condensed.

The critical temperature of methane is -116.6°F (-82.6°C). Adding small amounts of propane will result in a cricondentherm that gradually increases above -116.6°F. A complete study of the phase equilibria for the methane/propane system will reveal the maximum amount of propane that can be added without creating a cricondentherm that is higher than the defined minimum operating temperature for a super-fuel system. It was not possible to carry out such a study within the constraints of this project. Figure 3 would indicate that no more than about 10 mole percent (23.4 weight percent) propane could be added. However, this figure does not indicate how the allowable amount might be changed by narrowing the envelope of allowed operating conditions. For instance, if one accepts a higher minimum operating pressure, what happens to the allowable propane concentration? There may be acceptable tradeoffs available. Even if it is not possible to define a sufficiently large operating envelope exclusive of the two-phase region, the concept may still be viable provided the difference between liquid and vapor phase compositions does not become too great during the tank depressurization cycle. To explore the question somewhat further, a partial simulation of the methane/propane system was carried out using the ASPEN+ process simulation program. The simulation started with a tank containing propane at its vapor pressure, with 50% liquid, 50% vapor by volume. Methane was then bubbled into the liquid slowly until the tank pressure reached 3,600 psi. The changes in liquid level, and liquid and vapor compositions were plotted versus increasing pressure. The results are presented in a series of charts in Appendix A. Examination of Figure A-5, for example, shows that the equilibrium vapor phase at 40°F and 1,200 psi contains 18 mole percent (37.6 weight percent) propane. This would certainly be enough to make the super-fuel concept interesting. More extensive simulations of the system will be required to see whether the concept is actually practical. A number of isothermal composition paths need to be traced out in a series of thermodynamic cycle charts to see what the boundaries of composition would be for a stream removed from the bottom of a tank at constant temperature. Only then will it be possible to see what the practical limits of super-fuel composition would be, and therefore what benefits could be gained from its use.

The Multi-Fuel Engine

The difficulties of getting a conventional automotive engine to run at optimum conditions on more than one fuel have sparked research over many years on a variable compression engine design. Another reason for studying variable compression is the idea of being able to increase the compression ratio at part-load operation where the knock tendency is low. Improved fuel consumption in this operating range could then be expected (Seiffert and Walzer 1991). For compression ignition engines, the ability to use a higher compression ratio during startup improves starting characteristics (Grundy et al. 1976).

The U.S. Department of Defense has carried out considerable development on multi-fuel engines, because the very basis of defense depends on a guaranteed energy supply, particularly in the form of liquid fuels. Therefore it is desirable to have multi-fuel engines with the ability to operate on a wide range of hydrocarbon fuels (from gasoline to diesel, including shale oil or coal-derived fuels, with a wide spread of octane and cetane tolerance) in military vehicles without requiring physical adjustment or compromising engine performance or life (Rambie 1980).

Well-known is the idea of the BICERA piston, where the height of the piston top is varied hydraulically. Teledyne-Continental Motors developed such an engine as a replacement engine for the U.S. Army's XM-1 Main Battle Tank (Grundy et al. 1976). It maintains a constant peak cylinder pressure on different fuels by varying the compression ratio from 16:1 to 9:1.

In another approach, the combustion chamber of the conventional engine is divided into a main chamber and an auxiliary chamber. The volume of the auxiliary chamber can be varied by means of a floating piston. The concept provides for a complete close-off of the auxiliary chamber at the lowest part-load condition, while at full load the floating piston is withdrawn until a conventional compression ratio is reached. The volumes of the main and auxiliary chambers were selected in such a way that the compression ratio can be adjusted between about 9.5 and 15.0. The spark plug was positioned in the center of the floating piston and moved in and out with it. In this arrangement all auxiliary chamber pistons are moved simultaneously by means of a helical gear drive actuated by an electrical drive that is controlled by the throttle control mechanism.

To a certain extent, the effects of variable compression ratio can be achieved through supercharging or turbocharging.

COST ASSESSMENT

Obviously there are many unknowns about the potential cost of a flex-fuel CNG/LPG system. First, a gas composition sensor must be available. Current research at GRI and elsewhere should eventually make such a sensor available, but cost is completely unknown at this point. Presumably, series production should bring the cost into the same range as the cost of fuel sensors for the flex-fuel methanol/gasoline autos now on the market.

Second, an injector capable of operating on either CNG or LPG or any of their mixtures must be available. This seems technically feasible through modifications of either the GFI or the IMPCO approach. The end result should not be much more expensive than the current systems. An OEM-built CNG/LPG flex-fuel vehicle would not have a gasoline injector system, so the fuel injection system should be less expensive than for the current two-fuel CNG/gasoline vehicles. It should not be appreciably more expensive than for current dedicated CNG vehicles.

It is assumed that tanks for CNG/LPG would be no more expensive than normal CNG tanks.

In comparison to a dedicated CNG vehicle, the CNG/LPG flex-fuel vehicle would require the addition of a fuel sensor, an LPG vaporizer, and an engine control system that might be more expensive.

FEDERAL EMISSION STANDARDS FOR GASEOUS FUEL VEHICLES

On November 5, 1992, EPA proposed standards for emissions from natural-gas-fueled and LPG-fueled motor vehicles and motor vehicle engines. The rules were to be effective for the 1994 model year. However, as of the writing of this report in March 1994, the rules have still not been issued in final form. Basically, EPA had proposed that emission standards for gaseous fuel vehicles be equivalent to those for other vehicles. An exception was made with regard to the total hydrocarbon (THC) standards because of the difficulty of meeting these standards in methane-fueled vehicles. The lack of an effective exhaust catalyst for methane is the problem. Therefore, EPA proposed that CNG vehicles be required only to meet a non-methane hydrocarbon (NMHC) standard. Light-duty LPG vehicles would be required to meet 0.41 grams per mile THC and light-duty CNG vehicles would be required to meet 0.25 grams per mile NMHC.

Not requiring gaseous fuel vehicles to meet more stringent emission levels than gasoline, even though they are capable of doing so, leaves open the possibility that manufacturers of such vehicles would fail to make them as clean-burning as possible. It seems likely that these standards will be tightened in the future.

CLEAN FLEETS PROGRAM

The CAAA created a nationwide program to introduce clean fuel vehicles (CFVs). By model year 1996, automobile manufacturers must begin producing at least 150,000 clean fuel cars and light-duty trucks per year under a California pilot program. For model years 1999 and thereafter, manufacturers must produce 300,000 clean fuel vehicles each year.

Beginning with 1998 models, fleets with 10 or more vehicles capable of being centrally refueled in the 22 smoggiest cities (the serious, severe, and extreme ozone nonattainment areas plus Denver, Colorado, for carbon monoxide nonattainment) must begin to buy CFVs. In model year 1998, 30% of new passenger cars and most categories of light trucks and vans bought for these fleets must be CFVs. The percentage rises to 50% of purchased vehicles in model year 1999 and 70% in the year 2000 and beyond. For heavy-duty vehicles (up to 26,000 pounds), including school buses and delivery vans, the phase-in stays a constant 50% of new purchases beginning in model year 1998.

The CAAA defines clean alternative fuels as methanol, ethanol, other alcohols, reformulated gasoline, reformulated diesel (for trucks only), natural gas, propane (LPG), hydrogen, or electricity. Because the program accepts reformulated gasoline, it is not an alternative fuels mandate.

To meet the clean fleet program requirements, vehicles must be certified to meet at least the California Low-Emission Vehicle (LEV) standard. All qualifying CFVs are proposed to be exempted from any time-of-day and day-of-week restrictions on vehicle travel.

INHERENTLY LOW EMITTING VEHICLES

As a sub-part of the clean fleets program, the Inherently Low-Emission Vehicle (ILEV) program proposes to offer additional exemptions from Transportation Control Measures (TCMs) in the affected cities. This program focuses on reductions in ozone precursors. An ILEV is defined as a vehicle that:

- Qualifies as a CFV
- Meets the California ULEV standard for NO_x
- Meets a low evaporative emissions standard without control devices
- Is not allowed to run on higher emitting fuels.

It is proposed that ILEVs be allowed to use High Occupancy Vehicle lanes and be exempt from certain other TCMs. Participation in the ILEV program is voluntary.

Two-fuel CNG/gasoline vehicles could not qualify as ILEVs because of evaporative emissions from the gasoline fuel system. CNG/LPG vehicles, either two-fuel or flex-fuel, could meet the evaporative emissions requirement because both fuel systems are totally enclosed. Meeting the ULEV standard for NO_x should be the only technical problem. The potential benefits to owners of having their vehicles qualify as ILEVs in the affected cities makes the concept valuable in the marketplace.

SAFETY CONSIDERATIONS

Both methane and propane are less likely to autoignite on hot surfaces than gasoline or diesel fuel and require higher energy for ignition. In the case of a leak or fuel spill, gasoline and propane are heavier than air and will collect and possibly burn at ground level. Natural gas is lighter than air and can collect in ceiling areas of garages and parking spaces.

The explosivity ranges of the different fuels in air are not greatly different (*Figure 16*).

Various safety assessments have been carried out, yielding the following general conclusions:

- The safety records of both CNG and LPG vehicles are good.

- Gaseous fuel leaks can pose a significant explosion hazard relative to gasoline in enclosed garages. All fuels appear safe in a well-ventilated public garage.

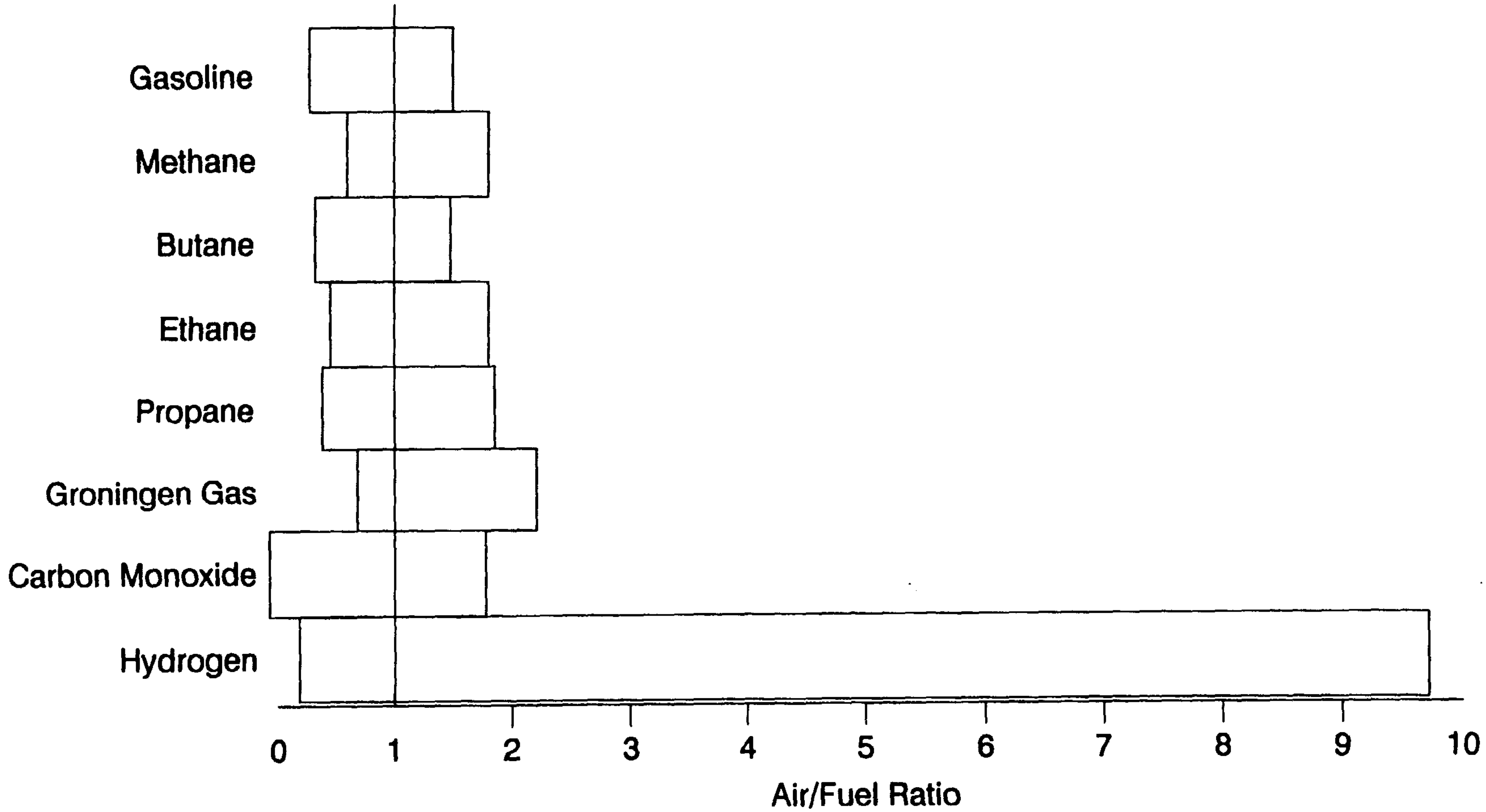
- For fuel line ruptures, pressurized gaseous fuels represent higher hazard levels than gasoline.

- In collisions, CNG is the safest fuel, LPG the next, and gasoline the worst.

On a technical basis, it appears that CNG and LPG are at least as safe as, and perhaps safer overall than gasoline systems.

The use of a two-fuel CNG/LPG system introduces no new hazards that are not present individually with CNG or LPG vehicles. It does create the possibility of fuel leaks that could accumulate either in the high areas or the low areas of poorly ventilated garages. Ventilation systems would have to be designed to handle both possibilities.

The only new hazardous element introduced by the flex-fuel CNG/LPG concept is the presence of LPG at a higher pressure than before. The pressure is of course no higher than that for other CNG systems. But a leak through a given size of hole at a given tank pressure will result in the release of material with more explosive power when the tank is filled with LPG rather than CNG. In this sense, the flex-fuel CNG/LPG system may be considered to be slightly more hazardous than either a conventional CNG system or a conventional LPG system.



Source: Klimstra 1986

Figure 16. Explosion ranges of mixtures of fuel gas and air

MARKET ASSESSMENT

The CNG/LPG vehicle can supply one niche of the total market for gaseous fuel vehicles. The first part of this market niche consists of those specific vehicle owners who otherwise would purchase two-fuel CNG/gasoline vehicles. There may be some potential among owners who otherwise would purchase dedicated LPG vehicles (they might consider the CNG/LPG vehicle as a way to use lower cost CNG without losing the range advantage of LPG), but this segment is believed to be small. Operators of dedicated CNG vehicles who are satisfied with their range limitations probably would see no reason to switch to a CNG/LPG system.

Vehicle owners in the targeted market segment are committed to buying CNG vehicles (because of fuel cost or environmental considerations or because of regulatory requirements) but are unable to accept the limited range. Therefore, they opt for a two-fuel CNG/gasoline system to solve the range problem. If propane were sufficiently available, and would adequately solve the range problem, it is believed that these buyers would accept a CNG/LPG system nearly as readily as a CNG/gasoline system. The percentage of total candidate CNG vehicle owners that would fall in this category is unknown, but based on the number of complaints received about limited range, it is believed that it could be as high as 30%. One or more of the CNG/LPG systems discussed in this report would appear to be capable of satisfying a broad range of customer desires. If 30% of all potential CNG vehicle owners would opt for such a system, it would seem to be worth developing.

It is estimated that by the year 2010 approximately 2 million fleet vehicles will be required to convert to alternative fuels under the mandates of either the CAAA or EPACT. Approximately half of these are likely to be CNG vehicles. If 30% of the these CNG vehicle owners opt for a two-fuel CNG/gasoline version because of concerns about achievable range, this gives a target of 300,000 vehicles.

GRI has carried out extensive market analyses for natural gas vehicles. These analyses cover both mandated conversions and voluntary conversions. Their latest estimate (GRI 1994) is for a total of 5.2 million natural gas vehicles by 2010. If the same 30% potential factor is applied, this yields 1.56 million vehicles as the target market for CNG/LPG systems.

In addition to the market defined above, there is another market slice consisting of those owners who would not buy either a dedicated CNG vehicle or a CNG/gasoline vehicle (and therefore would not be included in the above numbers) but who would be enticed to buy a CNG/LPG vehicle because of its more favorable characteristics, such as qualifying for ILEV status. There is no realistic way to estimate the size of this market slice.

SUMMARY OF POTENTIAL BENEFITS

ENVIRONMENTAL BENEFITS

The potential environmental benefits per vehicle can be applied to the total number of vehicles in the target market segment (1.56 million). Environmental benefits per vehicle include:

- No evaporative emissions. Evaporative emissions occur from CNG/gasoline vehicles whether or not they operate on gasoline during the day

- Approximately 45% less smog formed for every mile operated on LPG instead of gasoline

- Lower global warming contribution when operated on LPG than when operated on either gasoline or CNG

- Lower emissions of air toxics when operated on LPG instead of gasoline.

The absence of evaporative emissions makes CNG/LPG vehicles eligible for classification as ILEVs. The benefits that are proposed to be awarded to voluntary purchasers of ILEV vehicles can make this a very attractive option.

EPACT IMPLICATIONS

Every gallon of gasoline that is replaced by domestically produced LPG contributes to meeting the goals of EPACT. If the LPG were imported, some energy security benefits would still accrue, because having a wider choice in sources of supply would be beneficial; but it is obvious that the major thrust of EPACT would not be satisfied. It is therefore of interest to examine whether capturing the potential markets outlined in this study would force an increase in LPG imports.

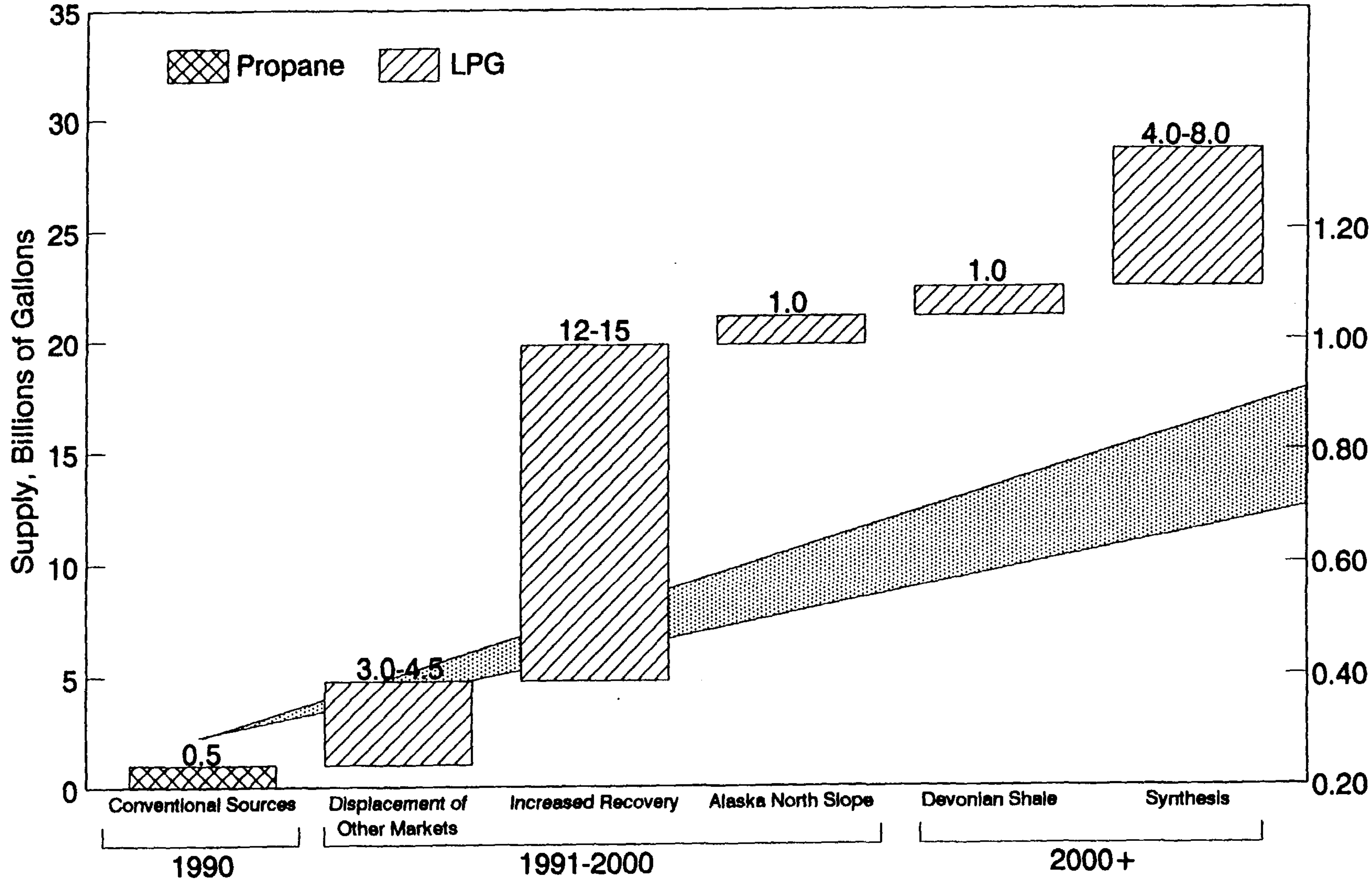
A market segment of 1.56 million two-fuel or flex-fuel vehicles has been identified. (Note that this market segment is entirely separate from the large number of dedicated LPG or LPG/gasoline vehicles that are expected). If LPG is used only as the range extender fuel, a usage rate of perhaps 15% could be assumed. If the super-fuel concept were to be successful at a level of 30% propane in the fuel, the usage rate could be 30%. This range of 15% to 30% LPG usage in 1.56 million light-duty vehicles could amount to a replacement of 175 to 350 million gallons of gasoline per year, requiring up to 470 million gallons of LPG. An analysis by Webb and Delmas (1991) shows that this amount is easily available within domestic supplies by simply shifting usage to other fuels in sectors such as petrochemicals where alternatives are easily available (Figure 17).

It can be concluded that an increase in automotive LPG demand within the dimensions outlined in this study is fully compatible with the goals and intent of EPACT.

ECONOMIC BENEFITS

At currently low gasoline prices, and high tax rates on LPG, there is not a large fuel cost savings for switching from gasoline to LPG unless the buyer is located in a low-cost LPG area or in a state where state tax policies are favorable. Current federal road taxes are $0.184 per gallon on gasoline, about $0.055 per equivalent gallon for CNG and about $0.25 per equivalent gallon for propane. State taxes, when levied on a gallon basis, result in the same discriminatory ratio between gasoline and LPG. However, there would be a slight fuel cost savings in switching from two-fuel CNG/gasoline operation to two-fuel CNG/LPG operation.

A very preliminary operating cost comparison is shown in Figure 18. The figure was constructed by using current West Coast retail fuel prices from *Clean Fuel Vehicle Week* (Anon. February 1994), and non-fuel operating costs from Webb and Delmas (1991). It assumes a light-duty truck operating 25,000 miles per year at



Source: Webb and Delmas 1991

Figure 17. Estimated supply and cost of auto LPG
(billions of gallons and dollars per gallon)

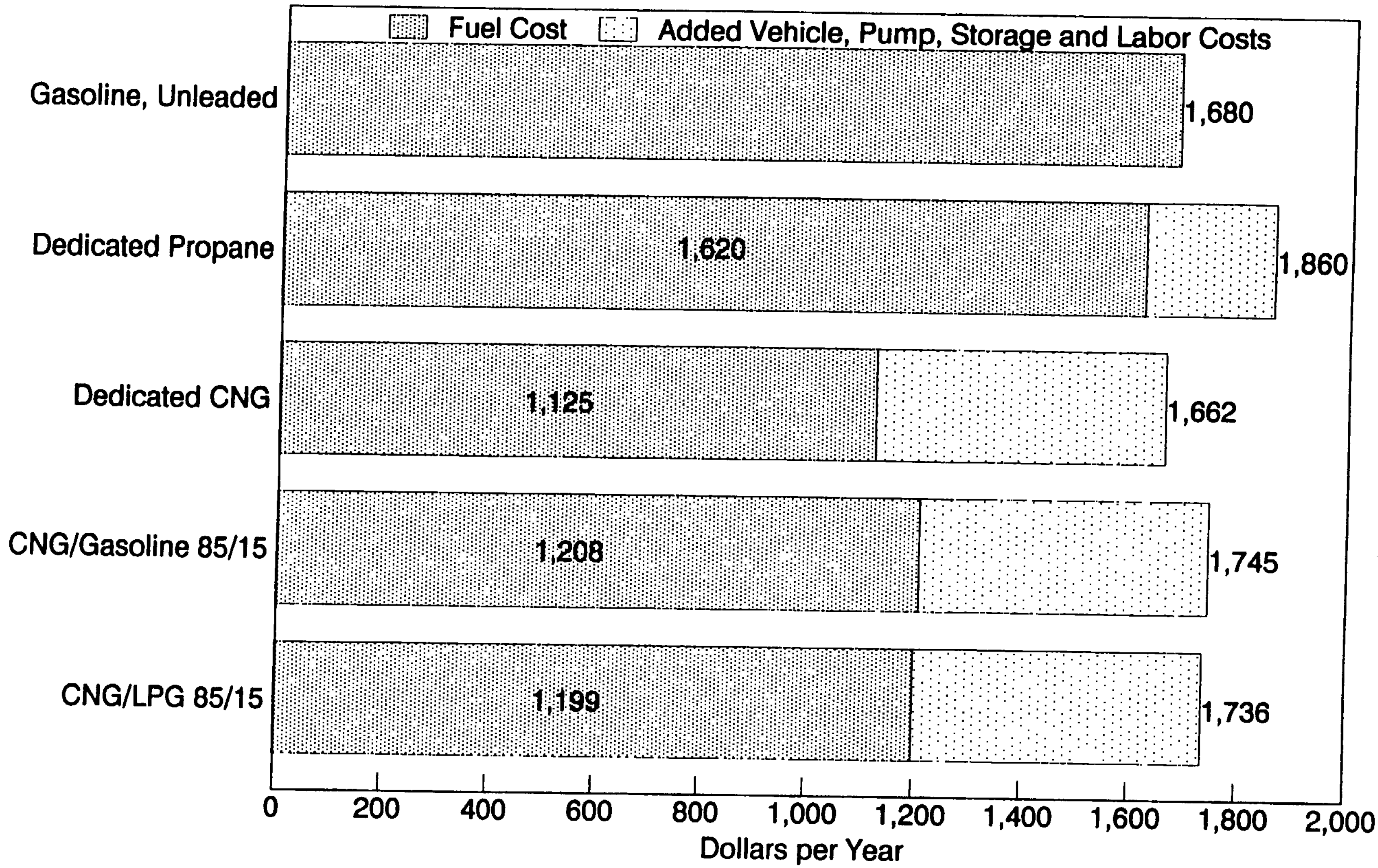


Figure 18. Preliminary annual cost comparison
(Light-duty truck, 1,500 gallons gasoline equivalent per year)

16.7 miles per gallon. It assumes that two-fuel CNG vehicles would operate 85% of the time on CNG and 15% of the time on the other fuel. It appears that two-fuel CNG/LPG operation would offer a slight economic benefit over two-fuel CNG/gasoline. In other regions with more favorable propane fuel prices the benefit could be considerably higher. This comparison assumes that a single gaseous fuel injector and engine control module were available so that the CNG/LPG conversion cost no more than the CNG/gasoline conversion. The comparison also does not take into account the tax deductions that are available to individuals under EPACT for the costs of alternative fuel vehicles.

REQUIRED RESEARCH AND DEVELOPMENT

TWO-FUEL CNG/LPG VEHICLE

This concept can be put in place today with certain limitations, namely a separate fuel injector for each fuel. To make the concept more economically attractive, a single injector capable of switching from one fuel to the other should be developed. This should not require a major expenditure of research and development funds.

FLEX-FUEL CNG/LPG VEHICLE

To create a practical CNG/LPG flex-fuel vehicle, the following hardware items must be developed:

- A gas composition sensor able to handle the full range of CNG/LPG mixtures
- A single fuel injector able to meter any combination of CNG/LPG mixtures with acceptable accuracy
- An LPG vaporizer compatible with CNG tank pressures and controllable to avoid heat input to the gas stream when not required
- An engine control system able to optimize performance, maintain emissions, and prevent knock with a wide range of fuel feed compositions
- An exhaust catalyst that will meet ILEV standards on both CNG and LPG
- A high-pressure (4,000-psi) liquid propane pump and dispensing system
- A fuel tank management system to protect against over-filling with LPG.

The long-term ideal solution for a CNG/LPG flex-fuel vehicle would be a variable-compression engine, or other engine concept, which would be capable of accepting any fuel or fuel mixture and burning it at the optimum compression ratio for that fuel. Such an engine would be expensive to develop, with uncertain prospects for success. Because of the limited market niche for the total CNG/LPG concept, there would be no justification for undertaking an expensive engine development program.

Before any hardware development efforts are begun, additional study of the thermodynamic properties of CNG/LPG mixtures should be carried out to determine:

- Compressibility of CNG/LPG mixtures in the critical region to evaluate potential over-filling hazards
- Variation in vapor-space compositions that would be used for stop-fill signal
- Variation of energy density of CNG/LPG mixtures with composition, temperature, and pressure
- Range of compositions possible when withdrawing material from tanks given different initial mixture compositions
- Effect of minor components of natural gas and commercial grade propane on all of the above.

SUPER-FUEL VEHICLE

Research and development requirements for developing the super-fuel concept--a fixed mixture of CNG and LPG--would be less extensive as far as the engine itself is concerned, because the allowable range of gas compositions would be far less. However, a gas composition sensor would probably still be required. A method of producing the required mixture composition and metering it into vehicle tanks at high pressure would have to be developed.

For the super-fuel concept it is even more important than for the flex-fuel concept that additional study of the thermodynamics of CNG/LPG be carried out before attempting any hardware development.

CONCLUSIONS

TWO-FUEL CNG/LPG VEHICLES

This study was undertaken to carry out a preliminary evaluation and assessment of vehicles using CNG and LPG on the same vehicle in various configurations. A review and evaluation of the literature demonstrates conclusively that there are both environmental advantages and energy security advantages to be gained from replacing two-fuel CNG/gasoline vehicles with two-fuel CNG/LPG vehicles. Such vehicles would have no evaporative emissions and could qualify as ILEV vehicles. Engine operation on CNG could be more nearly optimized than is the case for CNG/gasoline two-fuel vehicles.

There is no technical problem with two-fuel CNG/LPG vehicles that would be particularly worse than with current two-fuel CNG/gasoline and LPG/gasoline systems. If the CNG/LPG concept is to be economically competitive, it will be necessary to develop a universal CNG/LPG pressure-regulator-injector system and engine control module that can automatically accept a switch from one type of fuel tank to the other. Developing such a system is believed to be technically feasible without great expense or technical risk.

FLEX-FUEL CNG/LPG VEHICLES

The development of a CNG/LPG flex-fuel system able to accept an entire range of fuel compositions from all-methane to all-propane would create a more versatile system than the two-fuel approach. It would provide all of the same environmental and energy security benefits of the two-fuel approach while allowing vehicle operators freedom to choose the fuel mix that best satisfies their needs for every mission.

Several new hardware items would be required to implement the flex-fuel approach, starting with a gas composition sensor. However, work on composition sensors for variations in natural gas composition is already well under way. It should be straightforward to extend the technology to mixtures of CNG and LPG. High-pressure propane refueling pumps, suitable propane over-fill protection devices, CNG/LPG compatible vehicle fuel tanks, and a CNG-compatible LPG vaporizer must also be developed and/or tested.

Before starting any hardware development, further study of the thermodynamic properties of CNG/LPG mixtures should be carried out to delineate the exact range of operating conditions that would be encountered and the exact performance characteristics that would be required of the new equipment items.

A potentially promising concept has been described and is referred to as the super-fuel concept. It would be a mixture of methane and propane (CNG and LPG) with its composition defined to be within reasonably narrow limits. This would allow the development of engines that are efficiently optimized for operation on that fuel composition and that would also have a considerably greater operating range (perhaps as much as 40% greater) than dedicated CNG vehicles. The result would be a higher energy efficiency than any of the other systems described. At the same time, all of the environmental and energy security benefits of those systems could be retained.

The technical feasibility of the super-fuel concept cannot be judged until some basic analyses of phase behavior in the methane/propane system are carried out.

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APPENDIX A

Thermodynamic Charts

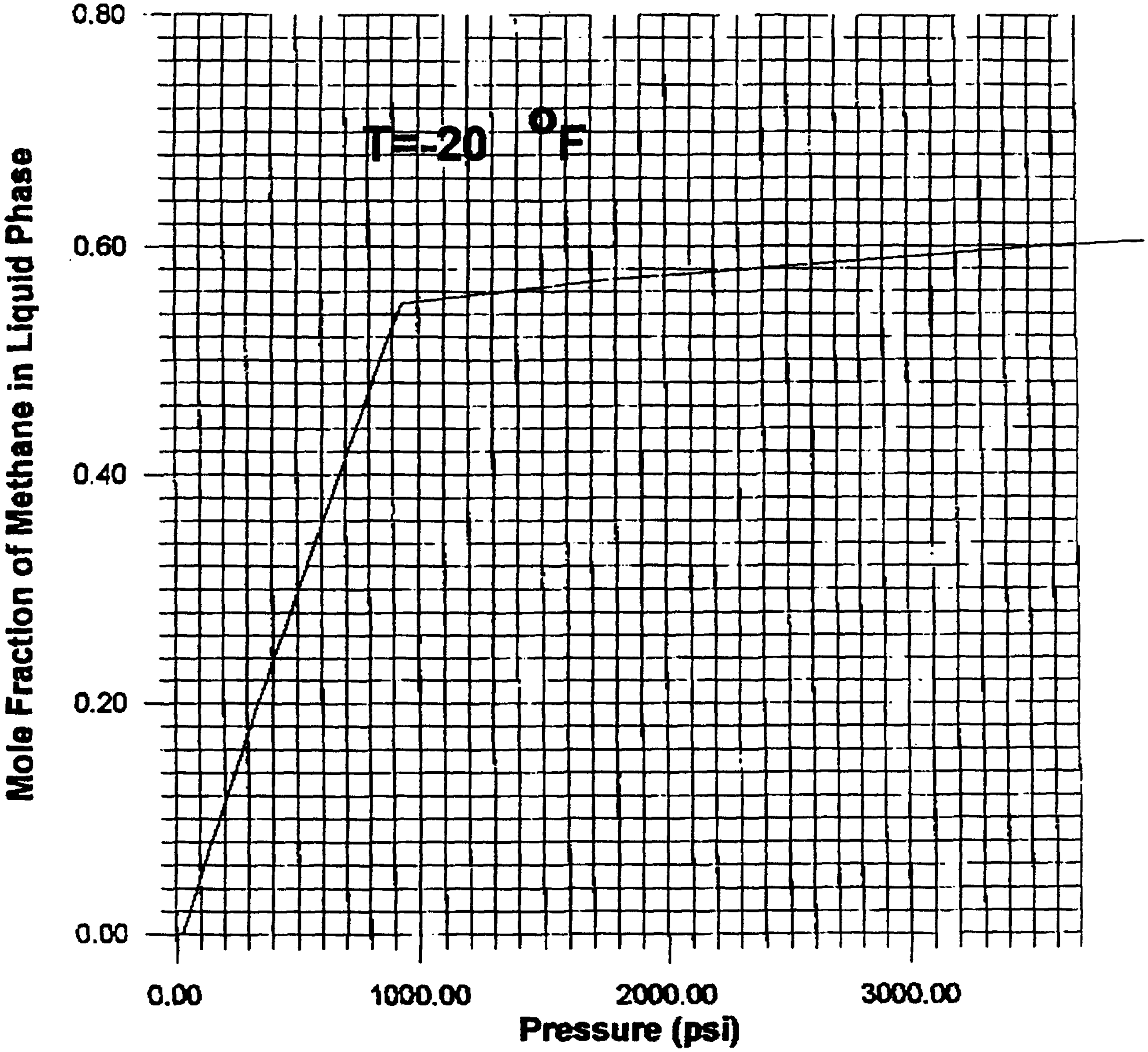

Figure A-1. Liquid composition versus pressure at T = -20°F

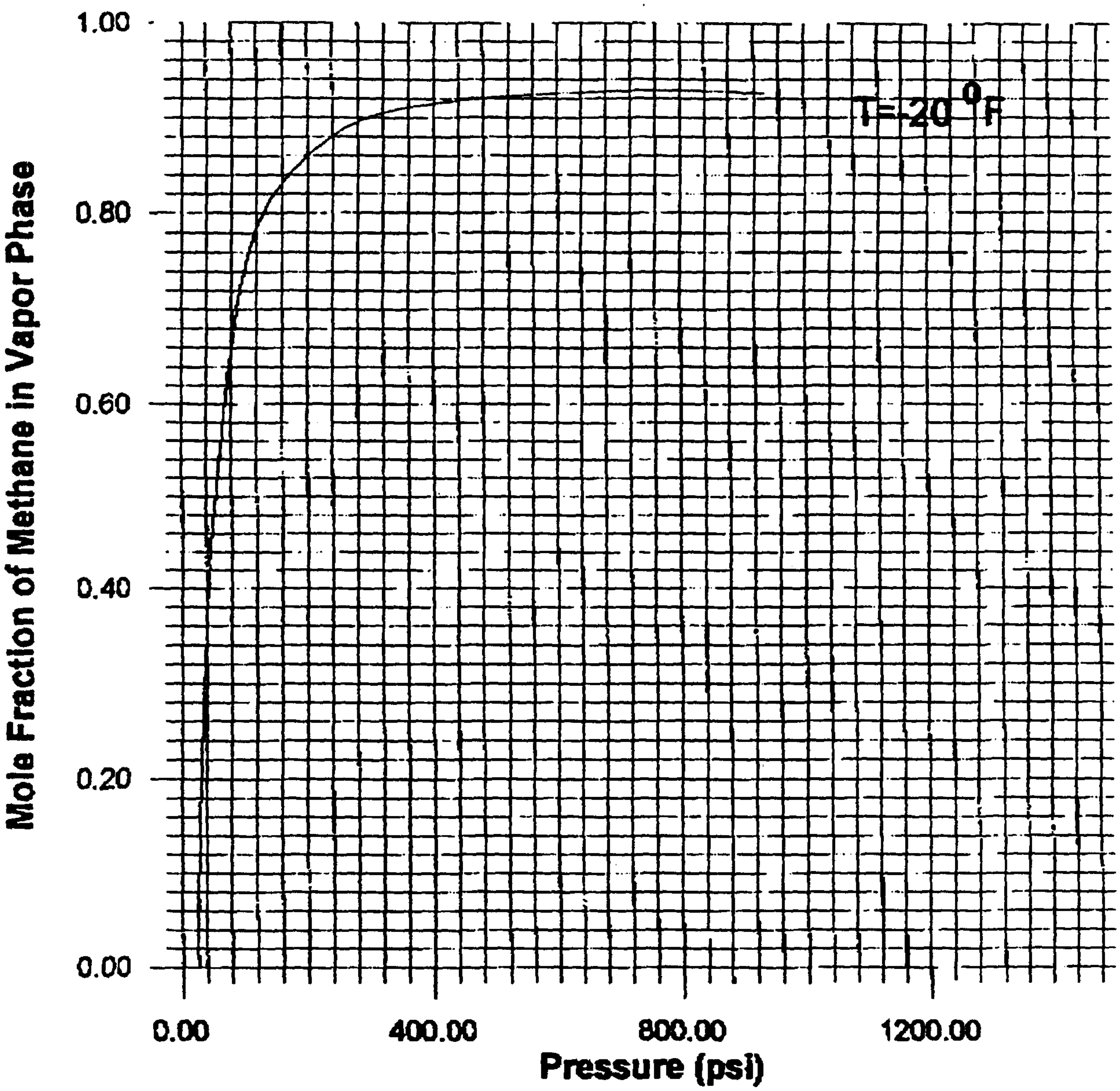

Figure A-2. Vapor composition versus pressure at T = -20°F

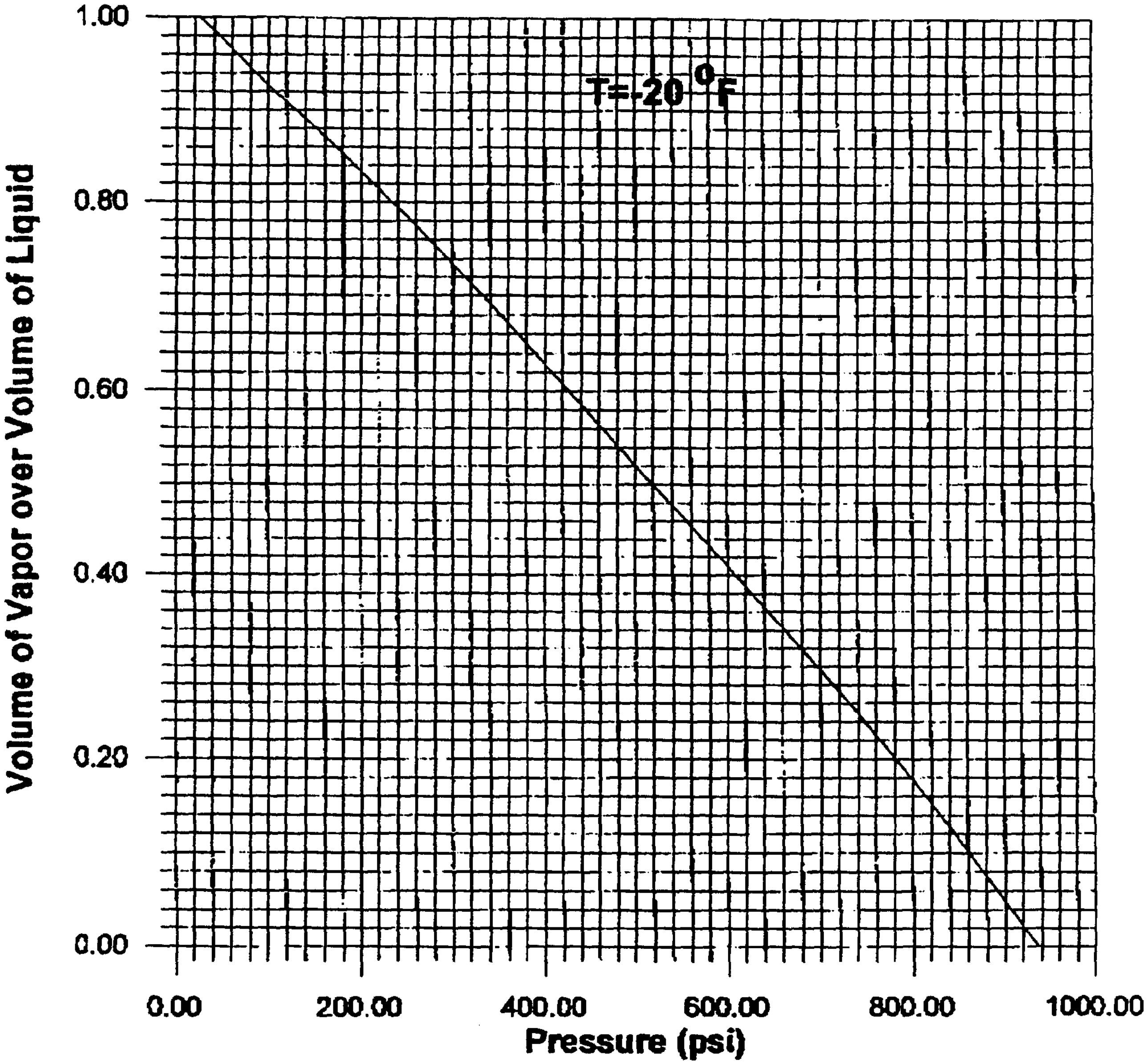

Figure A-3. Liquid level versus pressure at T = -20°F

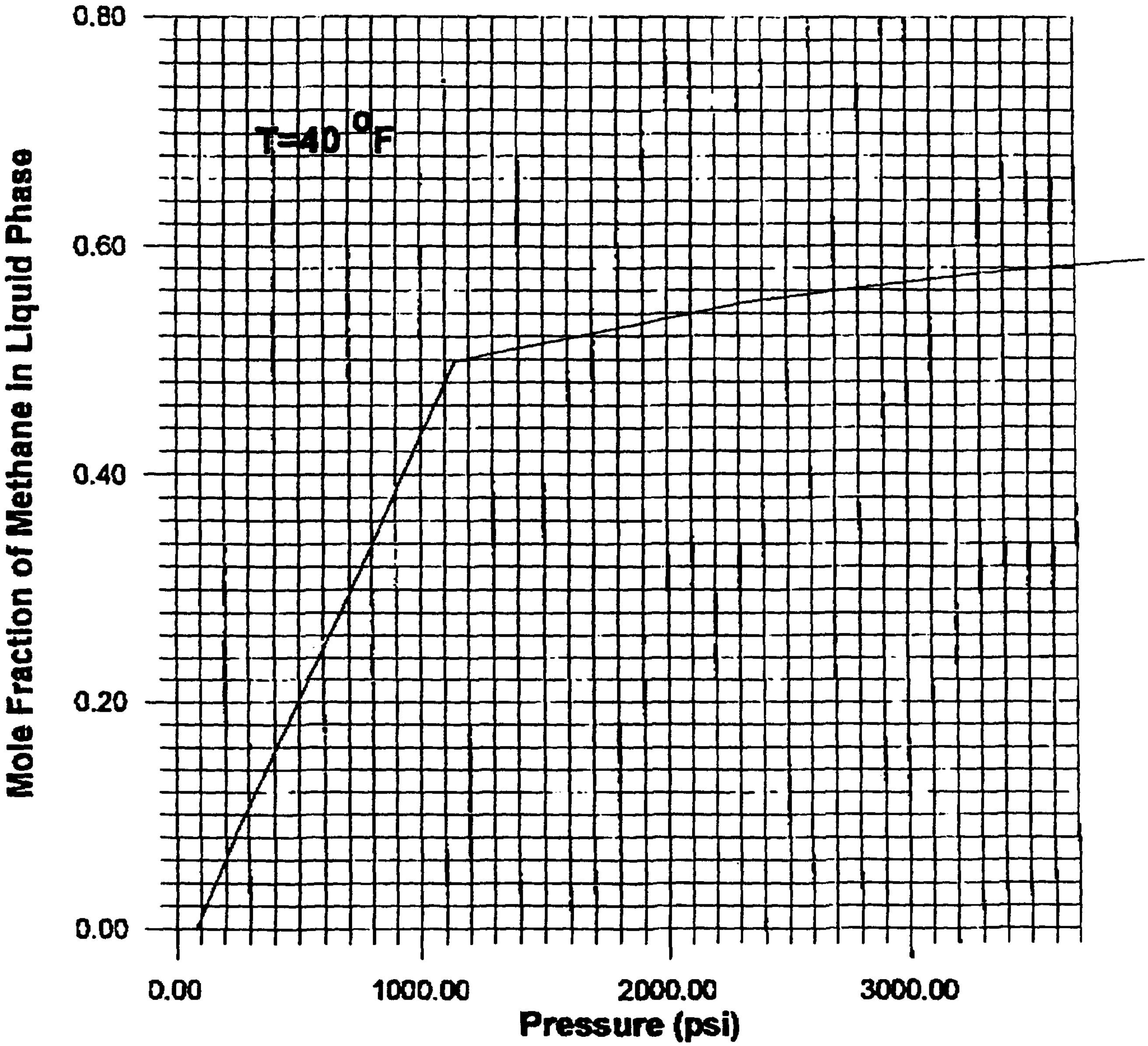

Figure A-4. Liquid composition versus pressure at T = 40°F

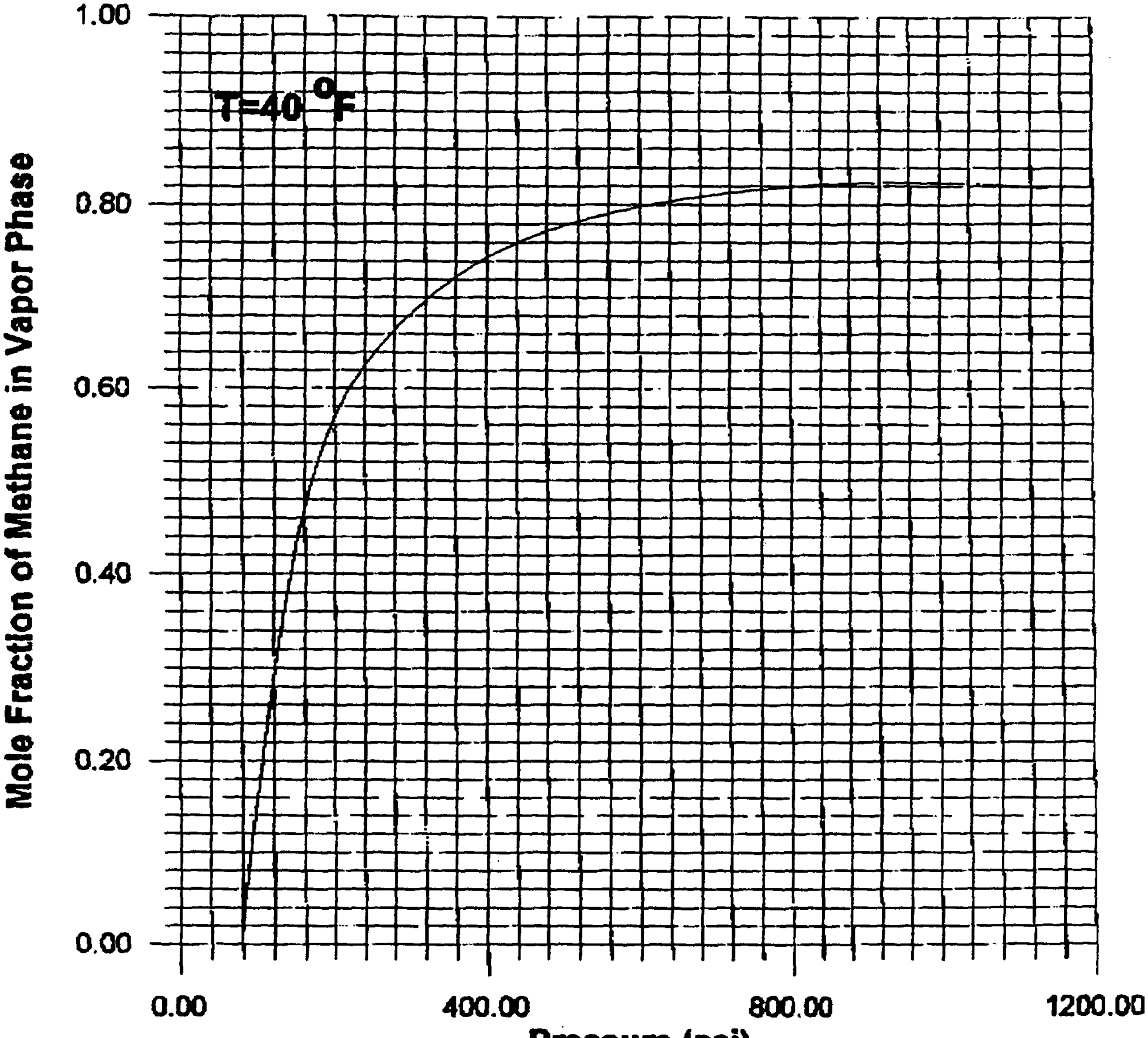

Figure A-5. Vapor composition versus pressure at T = 40°F

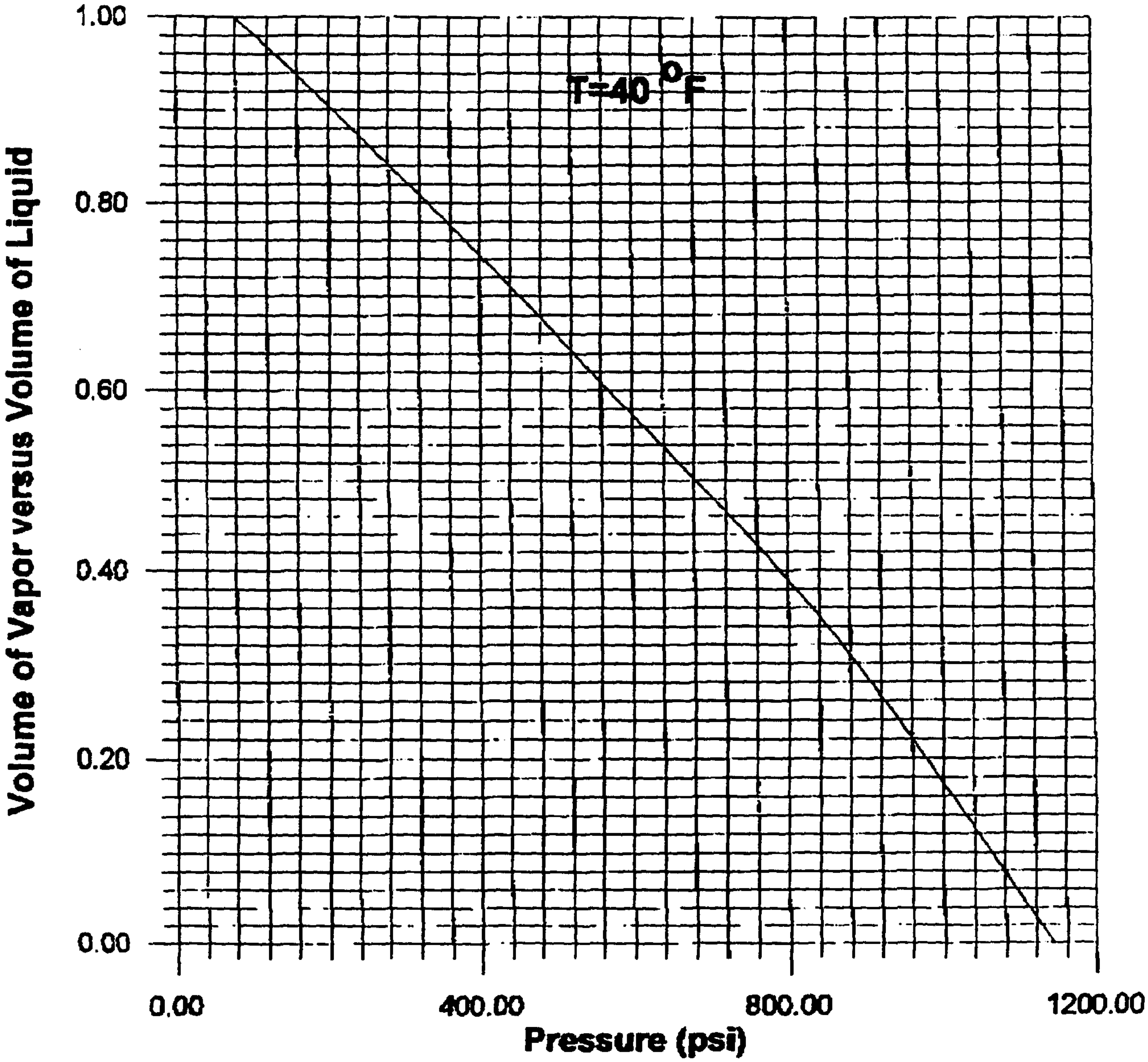

Figure A-6. Liquid level versus pressure at T = 40°F

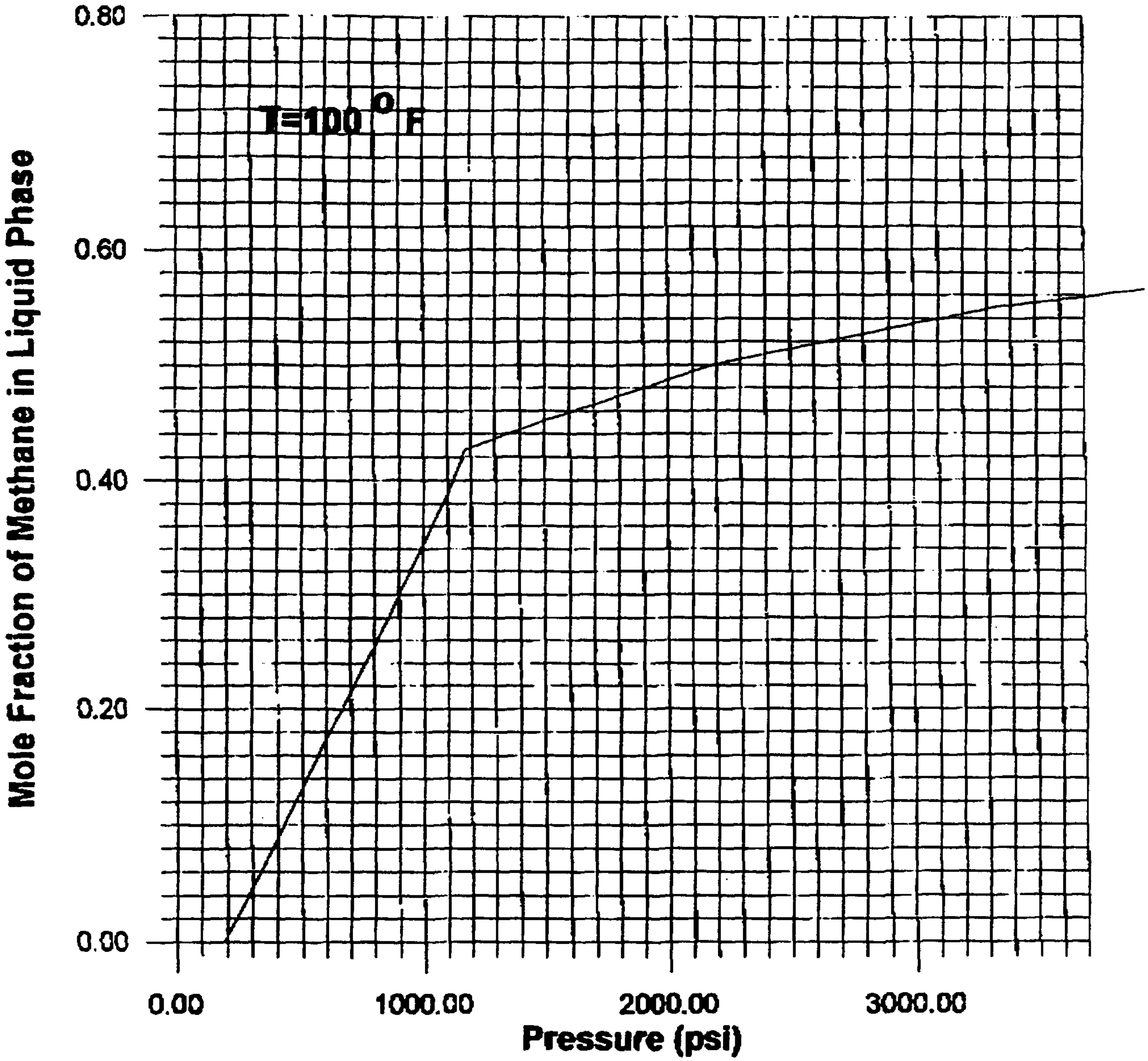

Figure A-7. Liquid composition versus pressure at T = 100°F

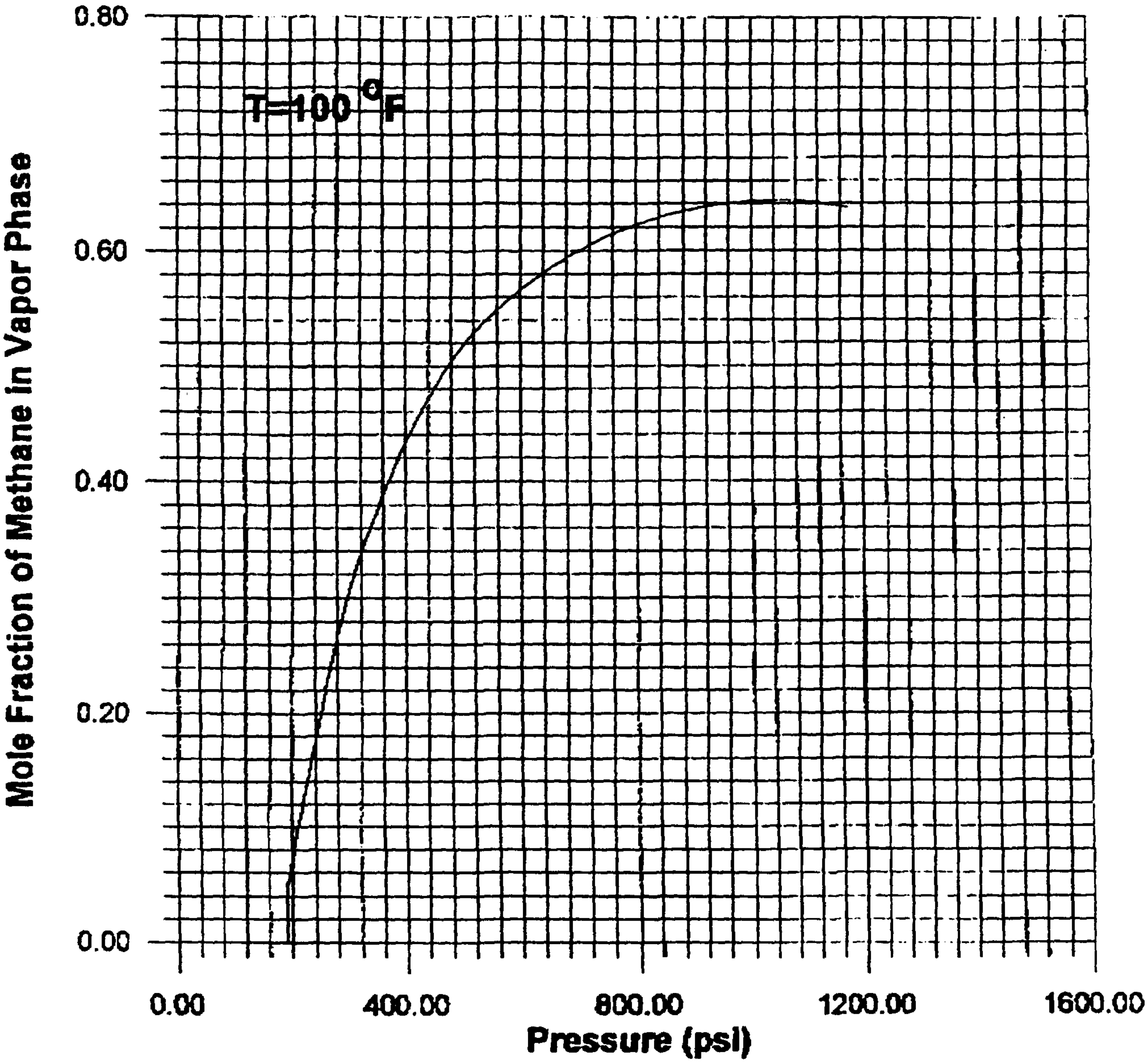

Figure A-8. Vapor composition versus pressure at T = 100°F

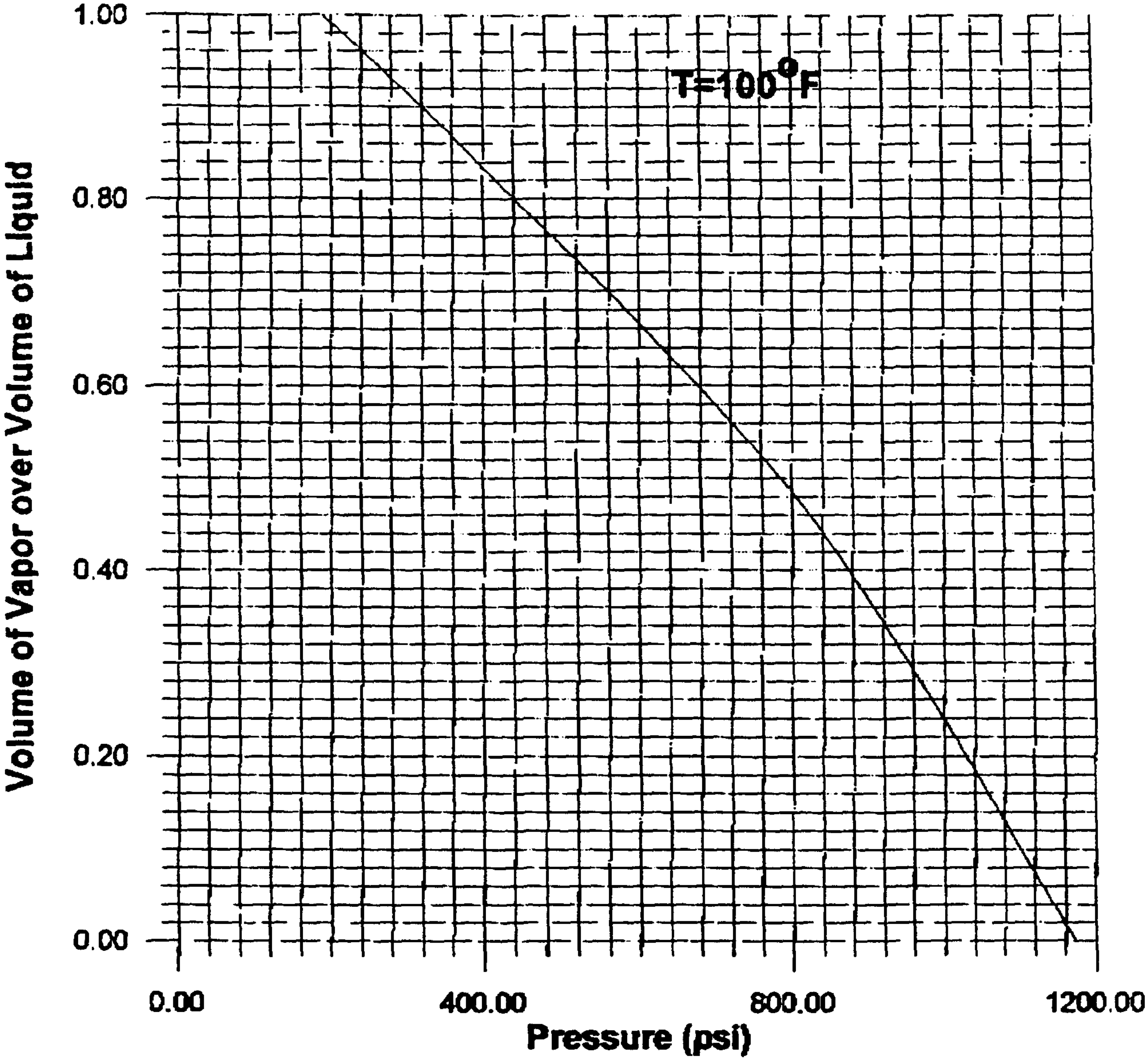

Figure A-9. Liquid level versus pressure at T = 100°F

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This report compares vehicles using compressed natural gas (CNG), liquefied petroleum gas (LPG), and combinations of the two in bi-fuel or flex-fuel configurations. Evidence shows that environmental and energy advantages can be gained by replacing two-fuel CNG/gasoline vehicles with two-fuel or flex-fuel CNG/LPG vehicles. For two-fuel systems to be economically competitive, it is necessary to develop a universal CNG/LPG pressure-regulator-injector and engine control module to switch from one tank to the other. For flex-fuel CNG/LPG designs, appropriate composition sensors, refueling pumps, fuel tanks, and vaporizers are necessary.

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